U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-285 782

# Utilization of Numerical Groundwater Models for Water Resource Management

Scientific Committee on Problems of the Environment, Paris (France)

Prepared for

Robert S Kerr Environmental Research Lab, Ada, OK

Jun 78

United States
Environmental Protection
Agency

Robert S. Kerr Environmental Research
Laboratory
Ada OK 74820

EPA-600/8-78-012
June 1978

PB 285 782

Research and Development

EPA

# Utilization of Numerical Groundwater Models for Water Resource Management

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

## TECHNICAL REPORT DATA
*(Please read Instructions on the reverse before completing)*

| | | |
|---|---|---|
| 1. REPORT NO.<br>EPA-600/8-78-012 | 2. | 3. RECIPIENT'S ACCESSION NO.<br>PB285782 |
| 4. TITLE AND SUBTITLE<br>UTILIZATION OF NUMERICAL GROUNDWATER MODELS FOR WATER RESOURCE MANAGEMENT | | 5. REPORT DATE<br>June 1978 issuing date<br>6. PERFORMING ORGANIZATION CODE |
| 7. AUTHOR(S)<br>Yehuda Bachmat, Barbara Andrews, David Holtz, and Scott Sebastian | | 8. PERFORMING ORGANIZATION REPORT NO. |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS<br>Scientific Committee on Problems of the Environment (SCOPE)<br>Holcomb Research Institute, Butler University<br>Indianapolis, Indiana 46208 | | 10. PROGRAM ELEMENT NO.<br>1NE625B<br>11. CONTRACT/GRANT NO.<br>Grant No. R-803713 |
| 12. SPONSORING AGENCY NAME AND ADDRESS<br>Robert S. Kerr Environmental Research Laboratory<br>Office of Research & Development<br>U.S. Environmental Protection Agency<br>Post Office Box 1198, Ada, OK 74820 | | 13. TYPE OF REPORT AND PERIOD COVERED<br>Final (6/75 - 9/77)<br>14. SPONSORING AGENCY CODE<br>EPA/600/15 |

15. SUPPLEMENTARY NOTES

16. ABSTRACT

The study assessed the present status of international numerical models as a tool for ground-water related water resource management. Among the problem areas considered are: the accessibility of models to users; communications between managers and technical personnel; inadequacies of data; and inadequacies in modeling.

The report, which is directed toward the nontechnical reader, describes 250 models. These are categorized as prediction, management, identification, and data management models.

17. KEY WORDS AND DOCUMENT ANALYSIS

| a. DESCRIPTORS | b. IDENTIFIERS/OPEN ENDED TERMS | c. COSATI Field/Group |
|---|---|---|
| Ground Water, Hydrogeology, Water Resources, Models | International | 48G |

| | | |
|---|---|---|
| 18. DISTRIBUTION STATEMENT<br>Release to Public. | 19. SECURITY CLASS *(This Report)*<br>Unclassified | 21. NO. OF PAGES<br>189 |
| | 20. SECURITY CLASS *(This page)*<br>Unclassified | 22. PRICE<br>A09 - A01 |

EPA Form 2220-1 (9-73)

☆ U. S. GOVERNMENT PRINTING OFFICE: 1978-757-140/1328 Region No. 5-II

ATTENTION

AS NOTED IN THE NTIS ANNOUNCEMENT, PORTIONS OF THIS REPORT ARE NOT LEGIBLE. HOWEVER, IT IS THE BEST REPRODUCTION AVAILABLE FROM THE COPY SENT TO NTIS.

EPA-600/8-78-012
June 1978

# UTILIZATION OF NUMERICAL GROUNDWATER MODELS FOR WATER RESOURCE MANAGEMENT

by

Yehuda Bachmat
Barbara Andrews
David Holtz
Scott Sebastian
Holcomb Research Institute
Butler University
Indianapolis, Indiana 46208

Grant No. R-803713

Project Officer

Jack W. Keeley
Ground Water Research Branch
Robert S. Kerr Environmental Research Laboratory
Ada, Oklahoma 748020

ROBERT S. KERR ENVIRONMENTAL RESEARCH LABORAOTRY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
ADA, OKLAHOMA 74820

## DISCLAIMER

This report has been reviewed by the Robert S. Kerr Environmental Research Laboratory, U. S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U. S. Environmental Protection Agency nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

# FOREWORD

The Environmental Protection Agency was established to coordinate administration of the major Federal programs designed to protect the quality of our environment.

An important part of the Agency's effort involves the search for information about environmental problems, management techniques, and new technologies through which optimum use of the Nation's land and water resources can be assured and the threat pollution poses to the welfare of the American people can be minimized.

EPA's Office of Research and Development conducts this search through a nationwide network of research facilities.

As one of these facilities, the Robert S. Kerr Environmental Research Laboratory is responsible for the management of programs to: (a) investigate the nature, transport, fate, and management of pollutants in ground water; (b) develop and demonstrate methods for treating wastewaters with soil and other natural systems; (c) develop and demonstrate pollution control technologies for irrigation return flows; (d) develop and demonstrate pollution control technologies for animal production wastes; (e) develop and demonstrate technologies to prevent, control or abate pollution from the petroleum refining and petrochemical industries; and (f) develop and demonstrate technologies to manage pollution resulting from combinations of industrial wastewaters or industrial/municipal wastewaters.

This report contributes to that knowledge which is essential in order for EPA to establish and enforce pollution control standards which are reasonable, cost effective, and provide adequate environmental protection for the American public.

William C. Galegar
Director

# ABSTRACT

The objective of the SCOPE International Assessment Project on Groundwater Model Modeling is an evaluation of the present status of numerical models as a tool for groundwater-related water resource management. During the course of the project, four major problem areas were identified:

1. Accessibility of models to users. Top priority should be given to making existing models more accessible to potential users as the most necessary immediate improvement. Increasing the accessibility of models consists not only in improving the quality of information about models and making this information and the models more available, but also in improving the training of those persons who use models.

2. Communications between managers and technical personnel. Measures must be taken to improve the links between management and those who provide technical services employing models. This will involve designing model outputs to be more responsive to management needs as well as more interactive participation by managers and technical personnel in problem definition and model applications.

3. Inadequacies of data. Solutions to problems of data will require increased attention to the identification of those data critical to the solution of groundwater management problems. Improved methods of data collection, storage, and retrieval are needed.

4. Inadequacies in modeling. In certain areas models still do not exist or are considered inadequate. The development or improvement of these models should be encouraged; in many instances, however, models will have to be preceded by improved scientific understanding of the fundamental processes which the models are to describe.

Specific recommendations for action have been formulated in each of these areas and are presented in the report.

This report was submitted in fulfillment of Grant No. R-803713 by the Scientific Committee on Problems of the Environment (SCOPE) under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period from June 1975 to September 1977. Work was completed as of September 30, 1977.

## TABLE OF CONTENTS

Foreword . . . iii

Abstract . . . iv

Acknowledgments . . . viii

CHAPTER 1 EXECUTIVE SUMMARY . . . 1

CHAPTER 2 CONCLUSIONS AND RECOMMENDATIONS . . . 3
- Accessibility . . . 4
- Communications . . . 5
- Data . . . 7
- Modeling . . . 9
- Concluding Remarks . . . 11

CHAPTER 3 DESCRIPTION OF THE PROJECT . . . 12
- Statement of the Problem . . . 12
- Origins and Organization of the Project . . . 13
- Project Aim and Scope . . . 14
- Project Audience . . . 15
- Project Methodology . . . 15
  - Survey of Groundwater Models . . . 16
  - Survey of Needs Related to Models and Their Use in Solving Groundwater Problems . . . 16
- Organization of the Report . . . 18

CHAPTER 4 MANAGEMENT AND MODELING . . . 19
- Groundwater-Related Problems . . . 19
  - Supply . . . 20
  - Contamination . . . 21
  - Environmental Impact . . . 21
  - Planning and Management Issues . . . 22
- Types of Management Decisions . . . 23
- Levels of Management Decisions . . . 24
- Management Levels and Modeling . . . 27
- Groups Involved in Modeling for Management . . . 28
- The Processes of Scientific Research, Model Building, and Model Application . . . 29

CHAPTER 5 THE GROUNDWATER SYSTEM AND GROUNDWATER MODELS . . . . . . . . 35

- Basic Characteristics of the Groundwater System . . . . . . . 35
- Man's Effect on the Groundwater System . . . . . . . . . . . 40
- Models Related to the Groundwater System . . . . . . . . . . 41
  - Prediction Models . . . . . . . . . . . . . . . . . . . . . 42
  - Resource Management Models . . . . . . . . . . . . . . . . 43
  - Identification Models . . . . . . . . . . . . . . . . . . . 43
  - Data Manipulation Codes . . . . . . . . . . . . . . . . . . 43
- Additional Comments . . . . . . . . . . . . . . . . . . . . . 44

CHAPTER 6 OVERVIEW OF EXISTING MODELS . . . . . . . . . . . . . . . . 45

- Introduction . . . . . . . . . . . . . . . . . . . . . . . . 45
- Model Characteristics . . . . . . . . . . . . . . . . . . . . 47
- General Comments . . . . . . . . . . . . . . . . . . . . . . 47
- Prediction Models . . . . . . . . . . . . . . . . . . . . . . 49
  - Flow Models . . . . . . . . . . . . . . . . . . . . . . . . 50
  - Mass Transport Models . . . . . . . . . . . . . . . . . . . 52
  - Heat Transport Models . . . . . . . . . . . . . . . . . . . 54
  - Deformation Models . . . . . . . . . . . . . . . . . . . . 54
  - Other Prediction Models . . . . . . . . . . . . . . . . . . 55
- Management Models . . . . . . . . . . . . . . . . . . . . . . 55
  - Groundwater Alone . . . . . . . . . . . . . . . . . . . . . 56
  - Groundwater and Surface Water . . . . . . . . . . . . . . . 56
- Identification Models . . . . . . . . . . . . . . . . . . . . 57
- Data Manipulation . . . . . . . . . . . . . . . . . . . . . . 59
- Model Usability . . . . . . . . . . . . . . . . . . . . . . . 59
- Concluding Remarks . . . . . . . . . . . . . . . . . . . . . 60

CHAPTER 7 GAPS IN MODEL APPLICATIONS TO MANAGEMENT NEEDS . . . . . . . 63

- Sources of Information . . . . . . . . . . . . . . . . . . . 63
- Categories of Gaps. . . . . . . . . . . . . . . . . . . . . . 64
- Accessibility of Models to Users . . . . . . . . . . . . . . 64
  - Model Documentation . . . . . . . . . . . . . . . . . . . . 65
  - Model Distribution . . . . . . . . . . . . . . . . . . . . 66
  - Training of Model Users . . . . . . . . . . . . . . . . . . 67
- Communications between Managers and Technical Personnel . . 68
  - Model Credibility . . . . . . . . . . . . . . . . . . . . . 69
  - Education of Managers . . . . . . . . . . . . . . . . . . . 70
  - Problem Definition . . . . . . . . . . . . . . . . . . . . 71
  - Acceptability of Management Models . . . . . . . . . . . . 71
  - Models in the Political and Legal Context . . . . . . . . . 71
- Deficiencies in Data . . . . . . . . . . . . . . . . . . . . 72
  - Data Collection . . . . . . . . . . . . . . . . . . . . . . 73
  - Parameter Identification Models . . . . . . . . . . . . . . 74
  - Data Manipulation . . . . . . . . . . . . . . . . . . . . . 74
  - Data Storage. . . . . . . . . . . . . . . . . . . . . . . . 75
  - Simple versus Complex Models . . . . . . . . . . . . . . . 75

CHAPTER 7 Deficiencies in Modeling . . . . . . . . . . . . . . . . . . . 76
Improvements in Existing Models . . . . . . . . . . . . . . 76
Prediction Models . . . . . . . . . . . . . . . . . . . . . 76
Stochastic versus Deterministic Models . . . . . . . . . 78
General versus Specific Models . . . . . . . . . . . . . . 78
The Role of Analog and Hybrid Models . . . . . . . . . . . 79
Institutions for Model Development . . . . . . . . . . . 79
Basic Research and Model Development . . . . . . . . . . 80

Establishing Priorities . . . . . . . . . . . . . . . . . . 80

APPENDICES
Appendix A REVIEW OF SURVEYED NUMERICAL MODELS............ 82

Appendix B LIST OF MODELERS ............................ 143

# ACKNOWLEDGEMENTS

Holcomb Research Institute gratefully acknowledges the work of Dr. Yehuda Bachmat, who served as project leader for this study while on leave for a year from the Hydrological Service of Israel. Dr. Bachmat, a ground water modeler, cataloged the models as they appear in Appendix A.

The Institute is particularly indebted also to Barbara Andrews, David Holtz, and Scott Sebastian for designing the project, and for researching and writing the report of the project with Dr. Bachmat. Barbara Goldberg, Bonnie Havholm, Carol Qualkinbush and Barbara Whitcraft ably assisted in all phases of the project.

The following members of the Steering Committee provided major contributions, active support, sustained interest, and valuable guidance to the project staff:

John D. Bredehoeft, U.S. Geological Survey, Reston, Virginia, CHAIRMAN
Harvey O. Banks, Consulting Engineer, Belmont, California
Jacob Bear, Israel Institute of Technology, Haifa, Israel
Patrick Domenico, University of Illinois, Urbana, Illinois
German E. Figueroa Vega, Comision de Aguas del Valle de Mexico, Mexico, D.F.
Yacov Y. Haimes, Case Western Reserve University, Cleveland, Ohio
Luis Lopez Garcia, INTECSA, Madrid, Spain
Don Lennox, Environment Canada, Ottawa, Ontario
Ghislain De Marsily, Ecole Nationale Superieure des Mines de Paris, France
George B. Maxey, Desert Research Institute, Reno, Nevada (deceased)
Jerome Milliman, University of Florida, Gainesville, Florida
R. William Nelson, Boeing Computer Services, Richland, Washington
David B. Oakes, Water Research Centre, Buchinghamshire, England
John R. Philip, Division of Environmental Mechanics-CSIRO, Canberra, Australia
Thomas A. Prickett, Illinios State Water Survey, Urbana, Illinois
Jehoshua Schwarz, TAHAL-Consulting Engineering Ltd., Tel Aviv, Israel
Tatsuo Shibasaki, Consulting Geologist, Tsurugashima, Saitama, Japan
Robert G. Thomas, Food and Agricultural Organization, United Nations, Rome, Italy
John Wilson, Massachusetts Institute of Technology, Cambridge, Massachusetts
Arnold Verruijt, The University of Technology, Delft, The Netherlands
Thomas F. Malone, Director, Holcomb Research Institute, Indianapolis, Indiana, (Ex Officio)
Ted Munn, Atmospheric Environment Service, Downsview, Ontario (Ex Officio)
Francois N. Frenkiel, Naval Ship Research and Development Center, Bethesda, Bethesda, Maryland, (Ex Officio)

# CHAPTER 1

## EXECUTIVE SUMMARY

The objective of the SCOPE International Assessment Project on Groundwater Modeling is an evaluation of the present status of numerical models as a tool for groundwater-related water resource management. Recommendations resulting from the project have been formulated to provide guidance to those persons and agencies interested in improving the utility of models to management. In the hope of reaching as wide an audience as possible, this report is directed toward the nontechnical reader.

The principal conclusions and recommendations of the project are set forth in Chapter 2. Four major problem areas are identified, and ranked by the staff and steering committee in the following order of importance:

1. accessibility of models to potential users
2. communications between managers and technical personnel
3. inadequacies of data
4. inadequacies in modeling

The project makes specific recommendations for action in each of these areas that are considered to be generally applicable to both developed and developing countries.

A complete statement of the project objectives as well as a history of the project and a discussion of its methodology is contained in Chapter 3. The project was carried out primarily through a series of surveys of two groups: 1) those most actively involved in development of models and 2) those active in application of models to management problems. The project staff also initiated a series of workshops which promoted discussion by professional experts of barriers to the more effective use of groundwater models. An international steering committee composed of scientists prominent in the development and application of models assisted the staff in these efforts. In addition the steering committee provided continuous guidance to the staff throughout the course of the project.

Chapter 4 describes groundwater-related problems and relevant management issues, and emphasizes the levels of management and the management decisions for which models are most appropriate. The chapter then explains for the benefit of the nontechnical reader, how the processes of scientific research and model building proceed and interrelate to produce models which can be applied to specific field situations. The relationships between scientific researchers, model builders, technical modeling experts, and managers are discussed.

For those readers unfamiliar with the field of groundwater modeling, Chapter 5 contains a simplified description of the natural physical systems which are described by models as well as a discussion of the impacts of various kinds of human activities on groundwater systems. The major categories of models which are used to describe and predict the behavior of groundwater systems are also introduced. The primary intent of this chapter is to help the nonspecialist become familiar with certain technical terms which may aid in understanding the project findings.

Chapter 6 presents a description and overview of the 250 existing models which were submitted in response to the project survey. The purpose, status, and application of models in each category are reviewed and summarized in a nontechnical manner. For professionals who are active in model development or who require models for the solution of management problems, a more detailed technical review of the surveyed models is presented in an appendix. In addition, a complete set of the responses to the model survey will be available from the National Technical Information Service in Springfield, Virginia.

Chapter 7 presents project findings regarding barriers to the efficient use of models as they are viewed by model users. This chapter also lays the ground for the project's conclusions and recommendations which represent a synthesis of the project findings by both the project staff and steering committee.

# CHAPTER 2

## CONCLUSIONS AND RECOMMENDATIONS

The recommendations of this report are intended to provide guidance to governmental and nongovernmental agencies at both a national and international level on measures necessary to improve the utility of models in groundwater management. During the course of the project, four major problem areas have been identified. These problem areas have been ranked by the project staff and steering committee in the following order of importance:

1. Accessibility of models to users. Top priority should be given to making existing models more accessible to potential users as the most necessary immediate improvement. Increasing the accessibility of models consists not only in improving the quality of information about models and making this information and the models more available, but also in improving the training of those persons who use models.

2. Communications between managers and technical personnel. Measures must be taken to improve the links between management and those who provide technical services employing models. This will involve designing model outputs to be more responsive to management needs as well as more interactive participation by managers and technical personnel in problem definition and model applications.

3. Inadequacies of data. Solutions to problems of data will require increased attention to the identification of those data critical to the solution of groundwater management problems. Improved methods of data collection, storage, and retrieval are needed.

4. Inadequacies in modeling. In certain areas models still do not exist or are considered inadequate. The development or improvement of these models should be encouraged; in many instances, however, models will have to be preceded by improved scientific understanding of the fundamental

processes which the models are to describe.

Specific recommendations for action have been formulated in each of these areas and are presented in the following sections. The recommendations have been conceived as broadly as possible and are intended to improve the utility of models in both the developed and developing nations.

## ACCESSIBILITY

Difficulties in the accessibility of existing models to potential users appear to be the most serious impediment to the effective use of models in groundwater management. Improved accessibility cannot be brought about through further research. Rather, shifts in the incentive structure of institutions or even modifications of the institutions themselves may be required. In general, the most important problems of accessibility revolve around issues of model documentation, model distribution, adequate training in the use of models, and in improving the simplicity of certification for the user. Each of these problems must be addressed in a different way.

Lack of adequate documentation emerges repeatedly as the primary stumbling block to more widespread and effective use of models in management. If a model is to be applied to more than one problem, a well-written and complete user's manual is essential. Unfortunately, the preparation of documentation is not necessary for the use of a model by its developer. In addition, documenting a model is a boring and usually unrewarding task. Finally, the preparation of documentation is a time-consuming and consequently costly task for which moneys are seldom available.

### Recommendation 1

> A prerequisite for the funding of model development by any public agency should be adequate documentation of a model produced. The documentation should include a description of the model, a listing of the code, and a user's manual.

Complementary to improved documentation of models is the need to develop means to distribute this documentation and to make potential users aware of what is available to them. Thus, some sort of central facility for providing information on the available groundwater models is necessary. Such a facility should ideally be internationally based with continued long-term financial support. If this proves impracticable, national centers should be encouraged. The consulting functions of such an organization should be limited; these can be provided by existing institutions.

Recommendation 2

> Models developed by public funds should be available to public agencies. A central "clearinghouse" should be established, to include all forms of documentation, information on the number and kind of problems for which the models have been tested and successfully used, as well as information on models commercially available.

The accessibility of models is constrained not only by the lack of proper documentation and inadequate distribution, but also by insufficient understanding on the part of technical personnel — often referred to as field hydrologists — of the capabilities of models. To some extent this deficiency is the result of the inevitable time lag between the development of a new tool and its widespread use. Models have been developed rapidly in recent years and the education of practicing hydrologists has not kept pace. This should be remedied through "short courses" and training programs.

Recommendation 3

> Encourage the development and/or expansion of programs designed to teach technical personnel how to better select and use models for addressing field problems as well as the capabilities and limits of newly developed modeling techniques. These programs should be especially directed at persons already practicing in the field.

COMMUNICATIONS

In improving the utility of models for groundwater management applications, better communication is an important priority. Three areas for improved communication have been highlighted: 1) between managers and technical personnel, 2) output of models, and 3) management models.

A gap in communications between managers and technical personnel is often found in the field of water resources which may cause unrealistic appraisals of model results. In these cases, two kinds of attitudes about models may be encountered among water managers. On the one hand, managers may be willing to accept any output of a model unquestioningly; on the other hand, they may distrust the model completely. The former attitude is bound to lead to disillusionment; the latter never gives the model a chance.

Such attitudes about models would appear to have three causes. First, there is considerable misunderstanding among managers about the way in which models work and consequently about the reliability and limits of model output. Second, managers are not easily able, and are sometimes unwilling, to state their problems to technical personnel in terms simple and concise enough to enable the proper use of a model to reach a solution. Third, modelers may be unable to communicate effectively with managers.

Generalized solutions to difficulties of misunderstanding and problem formulation are difficult to find; however, there are means to ameliorate the situation. Perhaps the most important of these is the increased involvement of managers in the process of modeling their problems. Managers will naturally develop more understanding and confidence in those problem-solving tools which they have helped to develop or apply. This is not to say that an attempt ought to be made to teach managers about the equations underlying the models or about computer programming. Rather, managers should be consulted frequently during the process of applying a model on such questions as the formulation of objectives and constraints, and the relative importance of various inputs or parameters. Equally important is the communication by technical personnel of relevant model results in language understandable by managers.

### Recommendation 4

> Encourage the interactive participation of managers and technical personnel in addressing groundwater management problems. In certain cases outside consultants may facilitate such interaction.

Often a barrier to the more effective utilization of models is their output. Managers need to have model results presented in a way that is meaningful to and compatible with decisions that must be made. The uncertainties contained in various decision alternatives are especially important to assess. The form of the output is also important. Careful use of graphics and other displays may greatly enhance the utility of model results.

### Recommendation 5

> The output of models needs to be formulated in ways that are useful to managers and which indicate the uncertainties contained in model results.

To date, the most effective management use of models has been in what might be termed "engineering decisions." On the other hand, the use of models in the formulation of policies and regional programs has in most countries been minimal. Nonetheless, management models for policy formulation do exist and have been used efficiently in some places. The fact that these models are not often used is largely due not to their lack of sophistication or accuracy, but rather to the fact that they are commonly, at least at the present time, not considered acceptable. This lack of acceptability is closely related to the institutions of water management and to the political context in which they function. However, as the scale and complexity of water problems increases there is clearly a growing need for the use of these models for policy decision making.

### Recommendation 6

> Encourage the utilization and further development of management models for the formulation of policies and regional programs where they are acceptable. Special emphasis should be placed on the participation of management in the formulation and utilization of such policy and management models.

## DATA

It is generally recognized that the reliability of the output of a model cannot exceed the reliability of the input data. These are often considered by model users to be seriously inadequate. On the other hand, there can never be enough data for a totally accurate prediction, and a supposed scarcity of data may serve to obscure a number of other difficulties in model application. Chief among these is the failure to consider what degree of accuracy in prediction is required of the model. This fact is particularly important in view of the typically high costs of data collection in comparison to other activities related to model development and operation due to the diminishing added benefit from collecting additional data.

Poor data do not make it impossible to use a model; they only influence the quality of the output. In those cases where a high degree of accuracy of prediction is not called for, a model with a minimum of data input may be sufficient. Where greater accuracy is required, sensitivity analysis can be conducted to determine which data are critical. The necessary money may then be spent on collecting these data.

### Recommendation 7

> Data collection for modeling purposes should be conducted in response to sensitivity analyses. Such analyses should include the value of benefits derived from collecting additional data.

Once critical data have been determined, these data should be collected at the least possible cost. As already mentioned, the cost of data collection represents a large, often the largest, single item in the budget for the analysis of a field problem. Thus, more cost-effective means of data collection could lead to substantial savings. Furthermore, data collection is, or ought to be, a continuous process for the updating or improving of a model over time. Eventually the sheer volume of data acquired for a region becomes cumbersome, and some form of centralized storage and retrieval becomes useful. Within the United States, the U.S. Geological Survey is developing a centralized computer-based cataloging and storage facility for data related to groundwater. The development and operation of such a facility should be encouraged in other places.

### Recommendation 8

> Improved methods of data collection on a routine basis should be developed. Particular attention should be given to the establishment of centralized storage and retrieval facilities.

## MODELING

The project finds that a surprising amount of activity has been directed, especially in recent years, toward the solution of a great many problems related to the modeling of groundwater systems. Models for most, although not all, problems that are of interest to groundwater management have been built. Naturally, some of these models are more satisfactory than others, but on the balance, the range of existing models shows a high degree of sophistication; most of the remaining problems in the description of physical systems are being investigated.

Several areas have been identified in which improvement of existing models is desirable. In general, these areas pertain to the modification of codes to facilitate their use and to allow greater transferability among users. Thus some models, although well documented, contain so many options that only a user very familiar with the program can use it effectively. Other programs are not easily understandable which precludes a user from modifying them for his particular case. Often including an example problem in the documentation of a code makes it more readily usable. Imaginative input and output routines facilitate use as well. Output routines which make the results easy to visualize and understand also increase the usefulness of a model.

### Recommendation 9

Every effort should be made to develop codes which are easy for the user to both understand and use. Improvement of existing codes is required in the following areas:

- simplicity of structure and use
- flexibility and visual illustration of outputs
- stability of outputs
- adaptability to other computers and codes
- computer storage and time requirements

Due to the volume of ongoing research and development in the field of groundwater modeling, it has proved difficult to evaluate just which kinds of models are now developed to a satisfactory stage. Furthermore, the determination of what is "satisfactory" is in part related to the particular field problem being solved and in part a matter of professional judgment.

Nonetheless, it has been possible to arrive at some consensus among at least a large number of professionals that certain kinds of models are missing or inadequate.

Although most problems of saturated flow can be regarded as solved, two special cases remain to be adequately modeled. The first of these is flow through a media of secondary porosity such as the fracture systems or karstic formations; the second is flow for immiscible fluids such as oil and water. The oil, water, gas problem has received extensive consideration in petroleum engineering. These results can be transferred with some modification to groundwater problems. Flow models are also needed that better integrate surface flow and flow through the unsaturated zone with saturated groundwater flow. Contaminant transport models have advanced rapidly in recent years, but there is still a need for models which handle better both chemical and biological reactions. Also, the inclusion of socio-economic and ecological aspects will greatly improve the usefulness of models to management. Finally, the inclusion of random or stochastic aspects, particularly in regard to aquifer parameters, is important in assessing the reliability of model outputs.

### Recommendation 10

Further model development is called for in the following areas:

* flow in media of secondary porosity
* flow for immiscible fluids
* fully integrated surface, unsaturated, and saturated flow
* contaminant transport with chemical and biological reactions
* socio-economic aspects
* ecological aspects
* consideration of stochasticity
* parameter identification

In the case of a few phenomena, the development of models is being hindered by a lack of understanding of the physical processes to be modeled. That is to say, once these processes are adequately understood and described, their introduction into a model should present no insuperable difficulties. Several such phenomena have been identified, but among these the most important are in the area of the kinetics of chemical and biological processes, the transport of pollutants through the unsaturated zone, and effects of scale and heterogeneity on transport phenomena.

### Recommendation 11

Further research is needed to describe:

- the kinetics of chemical and biological processes in groundwater
- mass transport in the unsaturated zone
- the quantification of management objectives
- parameter identification methodologies
- the effect of scale and heterogeneity on transport phenomena

## CONCLUDING REMARKS

The preceding recommendations are not the only ones that could have been formulated on the basis of the information and opinions collected over the course of the project. Chapter 7 of this report presents the findings of the project and elaborates upon the basis for these recommendations. There are, no doubt, other extremely interesting problems for further investigation. Nonetheless, the staff and steering committee have made a careful effort to address recommendations to what they feel are the most central problems in the use of models for groundwater management; furthermore, we have attempted to rank these problems in the approximate order of importance.

This project has been primarily directed toward the improvement of groundwater management, not toward the advancement of science and technology. We hope the recommendations will assist others in formulating their objectives, and more importantly, that they will serve to increase the benefits from the world's groundwater resources.

# CHAPTER 3

# DESCRIPTION OF THE PROJECT

In recognition of the significance of groundwater problems, the SCOPE International Groundwater Modeling Assessment Project began in June, 1975, to assess the status of numerical models as an aid in groundwater-related water resource management. This chapter contains a statement of the problems associated with the utilization of models in groundwater resource management, followed by an overview of the project's organization, aims, scope, audience, and methodology.

## STATEMENT OF THE PROBLEM

The enlightened management of water resources is becoming increasingly important as shortages of water and deterioration in water quality affect growing segments of the world's population. Groundwater is being increasingly exploited as both a primary and supplemental source of supply in a variety of regions and nations. The attractiveness of groundwater is due in part to: the capacity of aquifers to store large quantities of water commonly with minimal loss; the reliability of groundwater for long-term or supplemental supply; the potential for subsurface storage of hazardous wastes; and the use of groundwater as a hedge against drought. However, because groundwater is essentially a hidden resource, its proper management is often difficult to achieve.

In view of the mounting importance of groundwater and the uncertainties associated with its use, the development and use of improved formal or mathematical tools are necessary to foster more efficient groundwater-related resource management. Numerical computer models represent one such tool which has considerable capability for aiding managers in making decisions related to the various uses, both actual and potential, of groundwater systems.

Numerical modeling of groundwater is a relatively new field which was not extensively pursued until the mid-1960s. Since that time, significant progress has been made in the development and application of numerical models for groundwater-related resource management. (Management is here defined to include planning, implementation, and adaptive control of policies and programs related to the exploration, inventory, development, and operation of water resources containing groundwater.) However, in spite of this progress, gaps still exist between the need for, and the existence and actual use of, groundwater models in management. The closing of these gaps can serve to improve the management of groundwater resources.

Consequently, it is necessary to identify those models which management needs but does not have, and to examine the reasons why management does not use certain available models, or does not find useful other models which are both available and applied. Accomplishing these tasks requires both a detailed examination of the intrinsic strengths and deficiencies of the models themselves, as well as consideration of a variety of other factors or circumstances which are not directly related to the models but which affect model use. This report undertakes to lay the foundations for a unified effort on the part of those who fund the development of groundwater models, researchers, practitioners, and users, to improve groundwater-related resource management.

## ORIGINS AND ORGANIZATIONS OF THE PROJECT

Initiative and partial funding for the groundwater modeling assessment project was provided by the U.S. Environmental Protection Agency (EPA). The EPA's interest in evaluating groundwater models was an outgrowth of the agency's jurisdiction over activities affecting groundwater quality. While its responsibility for groundwater is confined to the United States, the EPA was aware of the desirability of drawing upon the experiences of other countries. Therefore, to add a meaningful international dimension to the assessment effort, the project was sponsored by the Scientific Committee on Problems of the Environment (SCOPE), a subcommittee of the International Council of Scientific Unions (ICSU).

The Holcomb Research Institute (HRI) of Butler University, Indianapolis, Indiana, was charged with the responsibility of carrying out the modeling assessment project, as a result of the Institute's well-established working relationship with SCOPE. The Institute was an appropriate organization in which to house the project, since it had just completed a critical evaluation of the role of modeling in environmental decision making in the United States.[1] The groundwater modeling assessment study was viewed as a logical continuation of this joint SCOPE/HRI effort.

Staff leadership for the groundwater modeling project was provided by Dr. Yehuda Bachmat, who came to the Institute on a year's leave from his position as Director of Research of the Hydrological Service of Israel. To guide the HRI staff and to insure adequate international representation in the development of the project, an international steering committee was assembled and first convened in Indianapolis, in June, 1976. The committee was composed of twenty-two groundwater modelers and water resource consultants and managers from the United States, Israel, Australia, Canada, France, Japan, Mexico, The Netherlands, Spain, the United Kingdom, and the Food and Agriculture Organization of the United Nations. The committee was chaired by John Bredehoeft of the U.S. Geological Survey. (A roster of the project steering committee and staff can be found in the Acknowledgements of this report.)

## PROJECT AIM AND SCOPE

The objective of the project was to assess the utilization of numerical models in groundwater resource management. To achieve this objective, the project was directed toward answering two major questions:

1. What are the needs for numerical models to address significant groundwater problems and related management decisions?
2. What are the existing groundwater models, and to what extent are the models meeting these needs?

---

[1] Holcomb Research Institute, Environmental Modeling and Decision Making: The United States Experience. A Report for the Scientific Committee on Problems of the Environment. New York: Praeger Publishers, 1976.

By answering these questions, the project hoped to arrive at recommendations and priorities concerning measures to enhance the use and utility of models in groundwater-related water resource management. The scope of the project was confined largely to investigating those countries and agencies represented by the members of the steering committee.

## PROJECT AUDIENCE

While the immediate recipient of the report is the U.S. Environmental Protection Agency (EPA), it is expected that its contents will be of interest to model builders, model users, and decision makers in governmental as well as private organizations throughout the world concerned with groundwater resource management. Major users of the report will be the first two groups -- model builders and model users -- who desire access to information on the extensive work which has already been undertaken in groundwater modeling. However, this report is also addressed to a wider audience, including both water resource managers and others interested in the subject. In an effort to make the report more understandable to nonscientific readers or individuals not directly involved in modeling, an attempt has been made to restrict technical details to Chapter 6, which reviews existing groundwater models.

## PROJECT METHODOLOGY

The objective of the project, as previously described, was to review the present utilization of models in groundwater resource management. Meeting this objective required an examination of the current groundwater-related problems, the decisions involved in solving those problems, the needs for models to aid in making those decisions, and the existing models. The project was thus designed to gather information, through surveys and interviews, from three groups of individuals: those responsible for groundwater-related management problems and decisions (managers); those applying models to the analysis of problems in groundwater management (technical experts); and those developing models to help solve groundwater-related problems (modelers). Some individuals belong to more than one of these three groups. The difficulties in surveying the members of the first group -- the decision makers or managers -- are apparent; in view of limits in both time and resources, the efforts of the project staff were primarily directed toward gathering information from the technical experts and the modelers.

## Survey of Groundwater Models

The project's primary activity, a survey of the existing groundwater models, was based upon a questionnaire designed to facilitate an analysis of the capabilities of existing models. Each questionnaire requested detailed information on the particular model being described: general identification characteristics, the model's conceptual and mathematical framework, the computer program, documentation and availability of the program, past applications of the model.

The model questionnaire was widely distributed to groundwater modelers throughout the world. From this effort, 250 completed questionnaires were received, a figure judged to represent a reasonably comprehensive and illustrative coverage of the population of existing numerical groundwater models in the Western World. The results of the survey are presented in Chapter 6. A detailed review of the models is included in Appendix A.

## Survey of Needs Related to Models and Their Use in Solving Groundwater Problems

In addition to the inventory of models, the project placed emphasis on examining the application of models to tasks and decisions for solving groundwater problems. As part of this activity, inquiries were addressed to hydrologists, engineers, planners, consultants, and other technical experts involved in the analysis of existing groundwater problems. While occupying a variety of professional roles, these individuals provide a functional interface between the model developers on one hand, and the groundwater resource managers or policy makers on the other. Some of these technical experts are model developers themselves; some apply their own models to field problems.

In the United States, the survey of technical experts was undertaken in two ways. The first approach utilized a brief questionnaire designed to solicit evaluations and recommendations relating to both modeling needs and uses in water resource management (see Appendix B). Nearly 2,500 of these questionnaires were distributed in a mailing which covered federal agencies (U.S. Geological Survey, Bureau of Reclamation, Army Corps of Engineers, Environmental Protection Agency, Soil Conservation Service), state agencies in the water resources and related environmental fields, interstate river basin commissions, and professional societies (Technical Division of the National Water Well Association and Hydrology Section of the American Geophysical Union). Of the forms distributed, approximately 10 percent were returned and analyzed by the staff.

The second survey approach used in the U.S. involved an in-depth discussion of modeling needs and uses through a series of three workshops held in different regions of the United States. The first workshop was held in Las Vegas, Nevada, on March 2-4, 1977; the second in Denver, Colorado, on March 24-25; and the third in Tampa, Florida, on April 6-8. Each workshop was arranged by the Holcomb Research Institute in cooperation with: the Desert Research Institute of the University of Nevada for the Las Vegas workshop; the Denver office of the U.S. Geological Survey, Water Resources Division for the Denver workshop; and the Tampa office of the Southwest Florida Subdistrict of the U.S. Geological Survey, Water Resources Division for the Tampa workshop.

Several factors were considered in the selection of the workshop locations, such as the variety of groundwater-related resource problems in the area, the level of modeling activity being directed toward solving these problems, and the nature of the groundwater decision-making structure, in each region considered as a workshop site. Workshop participants were invited from universities, private consulting firms, and government agencies at all levels. In all, approximately 150 professional model users from 30 states were consulted regarding their views on modeling and model application to groundwater resource management.

While the technical experts in the United States were surveyed directly in the workshop and by questionnaire mailings, the task of corresponding with such individuals in other countries was undertaken by the appropriate member of the project's international steering committee. A workshop similar to those held in the United States was arranged for The Netherlands, France, and surrounding countries in April, 1977. Committee members in other countries were asked to conduct in-person interviews or distribute the survey questionnaire by mail. Approximately 85 professional model users and managers from 22 countries expressed their views regarding modeling needs and applications to groundwater resource management.

Organization of the Report

Chapter 4 presents a general description of groundwater resource problems and associated levels of management and decisions, along with a brief explanation of the processes of scientific research, model building and the application of models to real systems. In Chapter 5, a relatively nontechnical introduction to the physical groundwater system and groundwater models is provided. An intensive technical analysis of existing models follows in Chapter 6. Finally, based on the various surveys, the identification and analysis of gaps related to the use and utility of models in groundwater resource management is discussed in Chapter 7. From this discussion the project's conclusions and recommendations are deduced and presented in Chapter 2.

# CHAPTER 4

# MANAGEMENT AND MODELING

This chapter examines, in a nontechnical manner, the relationship between the various management decisions and the uses of models as a tool for decision making. A brief description of general categories of groundwater problems is followed by a review of the different types of management decisions which must be made in addressing these problems. The different levels of hierarchy at which decisions are made is discussed and those levels of management for which models have been most effectively utilized are suggested. Finally, we discuss the several groups involved in the development and application of models to problems, and how the processes of scientific research, model building, and model application, are generally conducted.

## GROUNDWATER-RELATED PROBLEMS

Water problems in general and groundwater problems in particular continue to grow in complexity and significance as population, agriculture, and energy development expand. For purposes of discussion, groundwater problems may be divided into three principal categories: supply, contamination, and other environmental impacts. Planning and management issues add a fourth important dimension to groundwater-related problems. In fact, most groundwater problems fall under more than one of these categories. Furthermore, groundwater problems are linked with more general water resource considerations and with legal, economic, and political influences. Therefore, an effective response on the part of management to groundwater problems must be based upon the recognition of the relationships among problems and the associated impacts which any given decision may generate.

The order in which the problems are discussed in the following paragraphs does not indicate any particular priority among the problem categories. Furthermore, although the text mentions specific localities as illustrative examples, it should be noted that all of the problems discussed occur in many areas around the world.

## Supply

Provisions of water is basic to nearly any organized water resource management effort. Problems of water supply arise from the need to provide water users with a safe and adequate amount of water at all times or upon a particular schedule of demand. Certain cities or regions rely on groundwater exclusively as a source of supply. Surface sources in many areas have provided the bulk of the water for man's use. Recently, however, increases in demand for water have gone beyond the capabilities of these surface sources and have led to a growing reliance on groundwater as either a primary or supplementary source of supply.

Groundwater reservoirs commonly provide a dependable source of supply due to their large reserves. However, a prolonged pumpage from a groundwater reserve well in excess of its renewable yield may result in the situation known as groundwater mining. Within the United States, groundwater mining is especially prevalent in parts of the West, Southwest, and High Plains where the annual replenishment of the groundwater system is greatly exceeded by pumpage to meet the water demands of growing urban communities and heavily irrigated agriculture.

Under conditions of groundwater mining an ultimate shortage of groundwater is possible, and indeed inevitable. However, even in the absence of mining, there may be other problems which restrict the development of groundwater supplies. For instance, difficulties in gaining access to existing groundwater supplies may have several causes. The first of these is the fact that groundwater reservoirs are hidden from view and may in some cases be difficult to locate, map, or describe with regard both to capacity and spatial extent. Second, even if the location and characteristics of the groundwater system are known, the groundwater may be of naturally poor quality requiring costly treatment processes before it can be used.

Most importantly, economic considerations may constrain access to groundwater through the costs incurred by land acquisition, well construction, and other activities associated with development. Problems of groundwater utilization may be the result of political or social resistance. This resistance often arises out of a general preference for traditional surface sources, proprietary rights, or a lack of understanding of the potential of groundwater for expanding existing community water supplies.

### Contamination

Contamination problems are related chiefly to the pollution of groundwater by man. Groundwater pollution is caused by waste disposal activities such as landfills, contaminant holding ponds, septic tanks, and deep well waste injection. Pollution also results from area-wide groundwater recharge from urban and agricultural areas. The actual constituents polluting groundwater include toxic chemicals, brines, chlorides, nitrates, oil, trace metals, and radioactive substances.

Another source of contamination, saltwater intrusion into coastal aquifers and the upward migration of natural salt water can be caused by groundwater pumping. Pumping lowers the freshwater head in the groundwater reservoir and allows saltwater to enter. Coastal saltwater intrusion is a serious problem along the coasts of many countries such as Mexico, Israel, Japan, and the United States, and its adverse effects may range from the pollution of an individual well to the destruction of entire coastal agricultural systems or urban water supplies.

### Environmental Impact

Several kinds of impacts on the environment are caused by extensive groundwater exploitation; these comprise a third major category of groundwater-related problems. A substantial environmental impact associated with the use of groundwater, and caused by overpumpage, is land subsidence. Subsidence is a gradual collapse of the land surface resulting from the lowering of groundwater heads by pumping. Subsidence is of special concern in urban areas where it may damage buildings, roads, and water and sewer mains, and cause increased flood and hurricane hazards.

A second type of groundwater-related environmental impact is waterlogging of soils. Waterlogging is common with irrigation. While this particular problem may not be as dramatic as land subsidence, it is still a nuisance which afflicts many areas. Irrigation projects throughout the world are plagued by drainage problems.

A third type of environmental impact relates to the general ecosystem. Groundwater provides the base flow to streams and often plays a predominate role in determining the quality of surface-water, especially at low flow. Thus, groundwater can have an important and direct influence on the health of vegetation and other living organisms over a wide area.

## Planning and Management Issues

An institutional framework for the planning and management of groundwater is essential in addressing those physical problems presented in the previous sections. These institutions must deal not only with the physical problems of groundwater but with the related economic, legal, social and political issues as well. Although water supply, groundwater contamination, and environmental impacts all obviously have planning and management components, it is instructive to examine as a separate category institutional aspects of groundwater management. It is more difficult to deal effectively with the institutional barriers which comprise planning and management problems than it is to find sound scientific solutions to physical groundwater problems.

In the area of water supply, political constraints may determine the feasibility of developing groundwater as a usable water resource. Legal restrictions also may hamper the efficient use of groundwater; in the United States, for example, outmoded water laws still fail to acknowledge the fundamental physical interconnection between surface and groundwater systems; commonly the present laws and/or their enforcement regulate the groundwater system as if its use had no effect on surface water.

In the area of groundwater quality, at least in the United States, current regulatory measures place considerably greater emphasis on controlling pollution in surface water than on protecting groundwater supplies. Relatively little action has been taken to ameliorate environmental impacts, although these problems have been extensively studied from a scientific perspective in those areas where they pose the greatest hazards to human welfare.

## TYPES OF MANAGEMENT DECISIONS

In managing groundwater resources and solving groundwater problems, the groundwater manager is typically confronted with making some or all of five key interrelated decisions, namely: feasibility, investment, policy, development, and operations.

In determining the feasibility of a particular groundwater development, the manager must consider the natural groundwater system and its response to stress. He must then decide whether or not the groundwater system can support, for example, a given level of pumpage for the time planned. In a case of groundwater quality, the manager may have to decide the least harmful area on which to establish a landfill. For this decision the manager needs a variety of information, including of course, whether or not the landfill might contaminate an associated groundwater system.

Based on the determination of physical feasibility, the manager must consider economic feasibility. For example, he must determine if the benefits of having groundwater as a source of water supply are greater than the costs of drilling and maintaining a groundwater supply. Next, he must determine what the investment should be. Once groundwater is established as a supply source, the manager commonly continues to be faced with decisions concerned with when and how large to make additional investments to further exploit a given groundwater supply.

After the feasibility of a particular management action has been determined and an appropriate investment decision made, the manager must formulate a policy to establish viable institutional channels or frameworks within which his actions can be undertaken. If developing groundwater as a source of supply is the issue under consideration, a policy must be established to state the conditions under which groundwater may be withdrawn. Additional policy questions might involve controlling interference effects on a nearby community's well field, or providing accompanying regulations to ensure the quality of the groundwater supply.

Finally, once a policy for groundwater exploitation is established, either the manager, or, more likely, technical personnel on his staff, must make detailed plans concerning how best to develop and operate the system with a view toward maximizing benefits or minimizing costs. Such decisions might include the preparation of an engineering design for a new field, as well as stipulations for running the system once it is constructed. Maintenance and follow-up activities such as monitoring and system control also fall under the category of operations-type management decisions.

It should be recognized that the manager, in formulating decisions relating to feasibility, investment, policy, development, and operations, is always faced with numerous constraints. In general, legislation sets the basic framework within which the manager must make his decisions. He must then contend with outside political pressures. Commonly, the public vocalizes its opinions and places constraints on decisions.

Once the manager arrives at a decision which may or may not satisfy the majority of those groups expressing their views, he is often still faced with such common constraints as limited funds, inadequately trained personnel, and insufficient time. This variety of constraints, in sum, limits the manager's ability to implement technically feasible solutions to groundwater problems.

## LEVELS OF MANAGEMENT DECISIONS

The management decisions affecting water resources are made by individuals as well as by a full spectrum of government agencies ranging from the local to the national and even international levels (Figure 1). While the jurisdictions of these agencies inevitably overlap, certain generalities can still be made regarding the nature of the decisions made at each of the levels. In general, any coherent scheme for managing water resources must constructively integrate the effects of decisions made at these various levels.

An example of a decision made at the individual level is the decision by a farmer whether or not to drill a well to ensure an adequate and dependable water supply for his crop. This decision will be based mainly on the farmer's previous experience with weather conditions, and on his weighing of the risk of drought against the capital expenditure required for the development of an irrigation system. An individual decision by itself does not normally have much impact on the total water system of an area, but a large number of individual actions may combine to affect the groundwater system in significant ways. The individual may be subject to

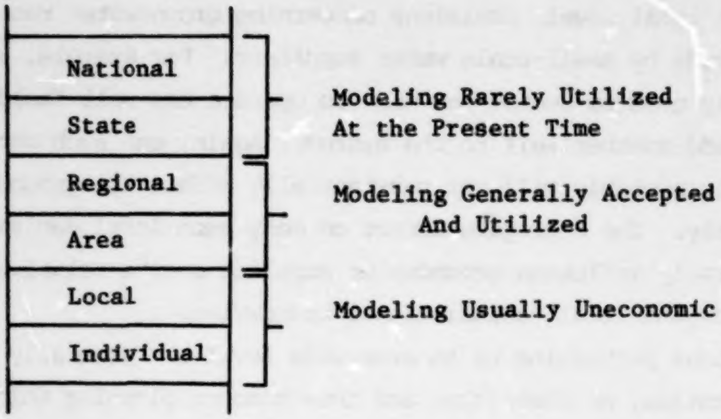

National
State
Regional
Area
Local
Individual
Modeling Rarely Utilized
At the Present Time
Modeling Generally Accepted
And Utilized
Modeling Usually Uneconomic

Figure 1. MANAGEMENT LEVELS

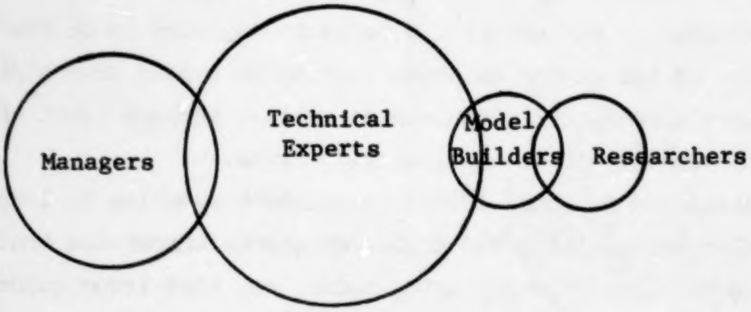

Managers
Technical
Experts
Model
Builders
Researchers

Figure 2. PROFESSIONAL GROUPS INVOLVED IN
MODELING FOR MANAGEMENT

a variety of constraints: well spacing regulations, well standard regulations, and water rights.

At the local level, decisions concerning groundwater resources are generally made by small-scale water suppliers. For example, a local water supplier may need to decide how best to operate his well field or whether or not to add another well to the system. Again, one such decision taken individually probably will not substantially affect the groundwater system significantly. The aggregate impact on many such local decisions may, however, adversely influence groundwater supplies over a relatively large area extending beyond local jurisdictional boundaries.

Decisions pertaining to an area-wide level are generally made by large cities, counties, or districts, and thus concern planning which is more comprehensive than that which occurs on a local basis. For example, a large city may need to decide whether or not to continue to rely on its surface water sources, or to begin to develop groundwater supplies if these are available. This level of management must make decisions such as where to develop the next well field, or where a major landfill might be sited so as to minimize the possibility of groundwater contamination.

At the next management level, regional authorities make decisions covering several county areas. Regional decisions affect mainly the impact of large-scale development projects or activities within an entire watershed. One relevant issue of concern at this level is methods of wastewater treatment. For example, a decision may need to be reached on the restriction of the number of areas relying on septic tank systems in order to protect groundwater resources as well as perhaps limit the haphazard expansion of cities into outlying areas.

At the state and national levels, government agencies in large countries deal chiefly with broad policy questions concerning their respective jurisdictions. A state water agency may thus issue guidelines and regulations concerning both quantity and quality aspects of ground and surface waters within the state. A state department of natural resources may decide whether or not groundwater is to be mined within the state, and what the lifetime of such a mining project might be expected to be.

National decisions consider such issues as interbasin transfers of water, and groundwater quality legislation which is binding on each individual state. It is important to note that the impacts of decisions made on one level on those of another level are not always recognized.

## MANAGEMENT LEVELS AND MODELING

The use of numerical models as an aid in decision making is more useful and effective at some decision-making levels than at others. For both the individual and the local water supplier, the commission of a modeling study to determine where to locate the next well is usually an uneconomical proposition. The individual or local supplier will understandably be unable or unwilling to expend thousands of dollars to model such a small-scale problem. He may, however, have access to a model maintained by an organization such as a university or extension service, which could be applied to his situation at a relatively modest cost. Nonetheless, in general, the use of models at the individual and local levels is uncommon.

At the present time, models are most widely applied to management decisions at the area and regional levels. Both the government agencies at these levels, and the groundwater issues with which they deal, are of a scale which makes computer modeling economically viable. To date, most groundwater modeling performed at these levels has pertained to engineering considerations affecting feasibility, investment, and operations decisions relating to particular, site-specific problems.

Modeling on a statewide and national basis is rare, but for obviously different reasons than those which explain the infrequent use of models by individuals and localities. The major cause of the infrequent use of models at the highest management levels is that the associated decisions deal primarily with policy rather than the more straightforward engineering problems. The formulation of policy necessitates interrelating physical or engineering factors with a variety of other considerations such as legal, economic, and political constraints. Models exist which attempt to do this, but, with the possible exception of Israel and France, they have not achieved widespread acceptance.

## GROUPS INVOLVED IN MODELING FOR MANAGEMENT

It is useful to consider the professional groups involved in developing and applying models. In general, four such groups can be identified, although considerable overlap may occur among them, and additional groups or "sub-groups" may also be present. These four groups are the managers or decision makers, the technical experts who use models, the model builders, and the scientific researchers (Figure 2).

The manager is the individual who is charged with solving a particular problem; ultimately, it is he who is responsible for commissioning and for paying the bill for a modeling study. The manager himself may decide that a model is necessary, or he may endorse a modeling study based on the advice of his technical staff. Many managers find it time-consuming or unnecessary to understand the technical aspects and implications of a modeling effort.

Because the manager may have little technical expertise in modeling or in the scientific aspects of a decision concerning the groundwater system, he must rely on a second group of professionals: the technical experts. The manager presents to the technical expert the problem at hand and the questions he would like addressed by the modeling study. The technical expert, who may be a member of the manager's staff or an outside consultant, chooses an appropriate model, applies it to the manager's problem, and interprets and presents to the manager the results of the modeling study. The interpretation of the model results is based upon the professional judgment of the technical expert, and thus the model results are only a component of his advice.

The technical expert, in adapting an existing model to a designated field situation, is actually dependent upon the original model builder who is a member of a third professional group. In relatively infrequent cases, occurring most commonly in private consulting firms, the model builder and the technical expert is a separate individual who relies on written documentation of certain models or on personal communication with the model builder himself.

Just as the technical modeling expert usually needs a model builder, so does the model builder require the input of a fourth professional group:

the scientific researchers. Normally the model builder and theoretical researcher are distinct individuals who come into contact either through established publications or personal interaction. The need for interdisciplinary cooperation is especially significant in scientific research on groundwater because such research requires inputs from a diversity of fields including geology, hydrology, chemistry, physics, civil engineering, and ecology.

The above discussion illustrates that the process of creating and applying a model to a management problem involves a series of groups. The links between these groups are not always good, and the failure of any one of them may adversely affect the utility of a model.

## THE PROCESSES OF SCIENTIFIC RESEARCH, MODEL BUILDING, AND MODEL APPLICATION

The preceding section describes and comments upon the relationships between four key groups involved in the use and development of models: managers, technical modeling experts, model builders, and scientific researchers. It is thus appropriate at this point to examine in a more detailed but nontechnical manner how the procedures of scientific research, model building, and the modeling of a real system, actually operate and interrelate. These procedures are discussed in an order opposite from that used to describe the four groups, since scientific research usually precedes model building which itself must occur before the modeling of a real system in the field can actually take place.

It should be noted that a fourth procedure -- that of the manager actually utilizing the information generated by the modeling of a real system or problem -- is not specifically treated in this discussion, although references to the use of model results by managers have been made in preceding sections of this chapter. The fourth procedure is not explicitly treated here because model information is utilized in such a variety of ways, situations, and contexts, that no one standard method for incorporating model output into decisions exists. This does not imply, however, that managers would not benefit from the development of such methodologies.

The procedure of scientific research and the knowledge derived therefrom lie at the basis of any model building and application effort.

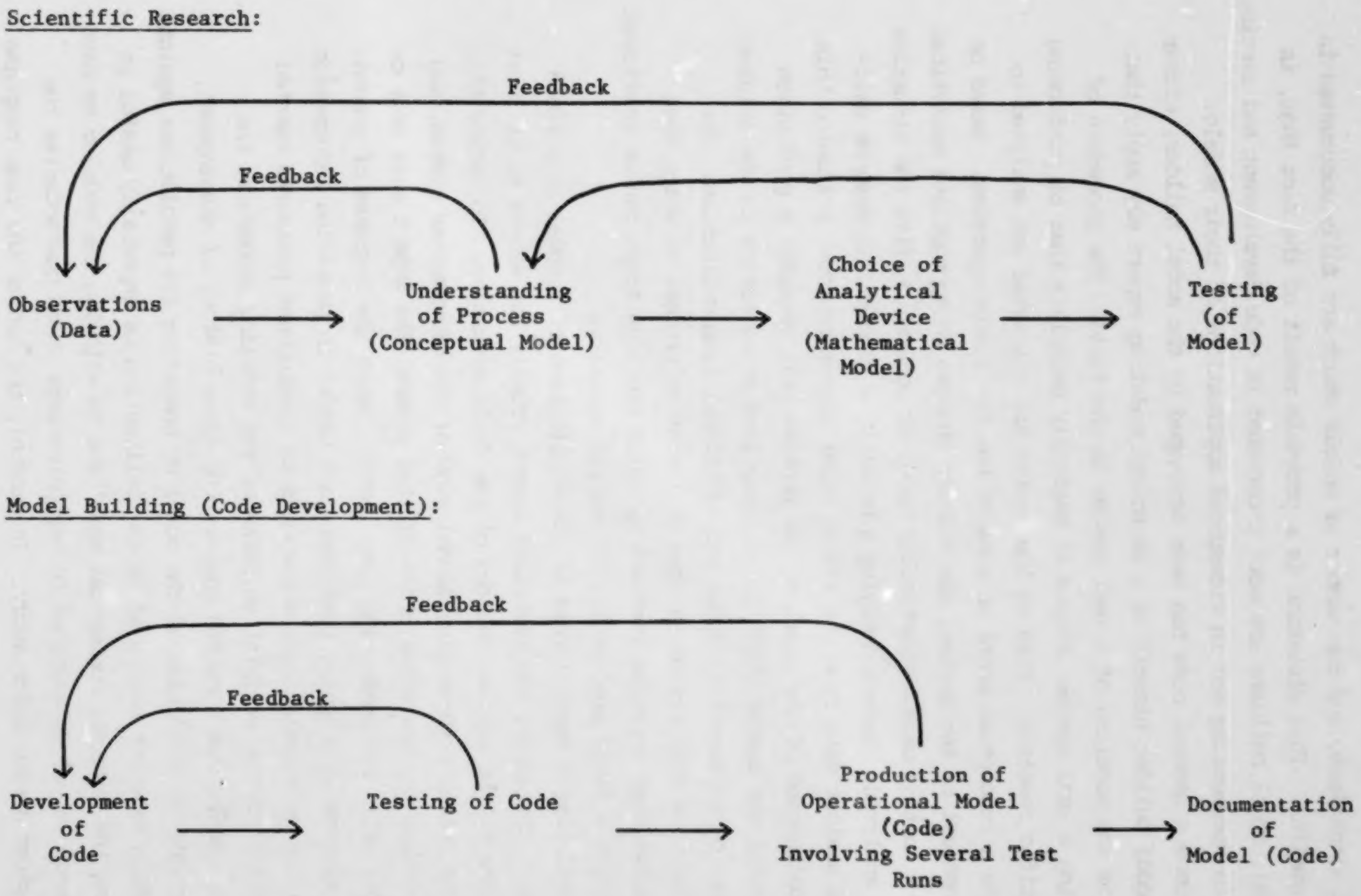
Scientific research begins with observations of a process to produce information on that process. This information, in turn, leads to some level of understanding of the process, on the basis of which a conceptual model of the process can be formulated or the original observations corrected or adjusted.

The conceptual model is, in essence, a theory of how the process operates in a certain environment. To gain more refined insights into the process, an analytical tool or device may be utilized, which in some cases may be a mathematical model. By means of this device or model, the scientific theory can be tested. The testing procedure, in turn, provides information or "feedback," which is used to modify the original observations and theory.

The various steps in the basic procedure of scientific research are outlined in Figure 3. It should be noted that the procedure is ordinarily repeated many times before a satisfactorily tested description of the process under study is achieved.

Once the process is understood it may be incorporated into a mathematical model; the next step is the construction of that model, again according to a series of several major, definable steps (Figure 3). Model building at this level should be regarded not as the creation of a specific model for a specific problem, but rather as the development of a general computer code which is based on the conceptual model. Once the computer code is developed, it is tested against hypothetical data, as well as against the underlying theory itself. The testing procedure yields feedback which is used to modify not only the code, but in some cases also the original theory as derived through the scientific research. After the code has been tested, it becomes operational, and can be further applied to selected field situations. Once a code has been made operational, it still must be made available through the production of documentation, that is, of adequate published material which describes the code and provides guidelines for its application to real-world problems.

At the present time, many of the existing groundwater models are in the stages of code development or testing; however, where testing has occurred, it typically has been undertaken only once or twice per model. Only a minority of models have been utilized for the analysis of several


Scientific Research:

Feedback
Feedback
Observations (Data)
Understanding of Process (Conceptual Model)
Choice of Analytical Device (Mathematical Model)
Testing (of Model)

Model Building (Code Development):

Feedback
Feedback
Development of Code
Testing of Code
Production of Operational Model (Code) Involving Several Test Runs
Documentation of Model (Code)

Figure 3: SCIENTIFIC RESEARCH AND MODEL BUILDING

field situations, and the number of models which are fully documented is even smaller. This situation is a probable result of the fact that, in general, model builders are more interested in code development and testing than in documenting and in widespread applications of their models.

Once a general code has been developed by the model builder, either the model builder himself or a technical modeling expert may apply that code to the modeling of a real system in the field. The procedure of modeling a real system (Figure 4) basically parallels that of performing scientific research. Data on the system are collected and analyzed to provide a conceptual model or idea of how the system operates. Based on this concept of the system, the modeler chooses an appropriate analytical tool — in this case, a particular model or code which fits the situation to be analyzed. Before applying a model to a problem, it must be calibrated against data from the system under investigation. Following this, the application of the model to the problem will generate a prediction concerning the system which in turn may lead to revisions in the original concept, or mathematical model and additional data collection. The modeling of a real system is thus an iterative process in which each successive step provides feedback by which previous steps can be readjusted to produce a final predication of desired accuracy.

Data play a central role in the application of a model to a field problem. Initially, the technical expert usually has access to at least some data on the surface geology of the field situation. To refine this data, to obtain a three-dimensional view of the groundwater system, and to ascertain key characteristics of that system, the expert must rely on drilling wells and conducting pump tests. Since the response of groundwater systems is dynamic, pump tests are useful in providing information on how the groundwater system responds to development pressures exerted over time. In the calibration phase of the modeling procedure, the model's results are compared against the known history of development. Furthermore, a validation of the model by comparing its predictions against data which have not been used in the calibration is especially useful in refining the original conceptual model and in allowing the modeler to have confidence in values assigned to key parameters which characterize the groundwater system under study. In general, the longer the time response

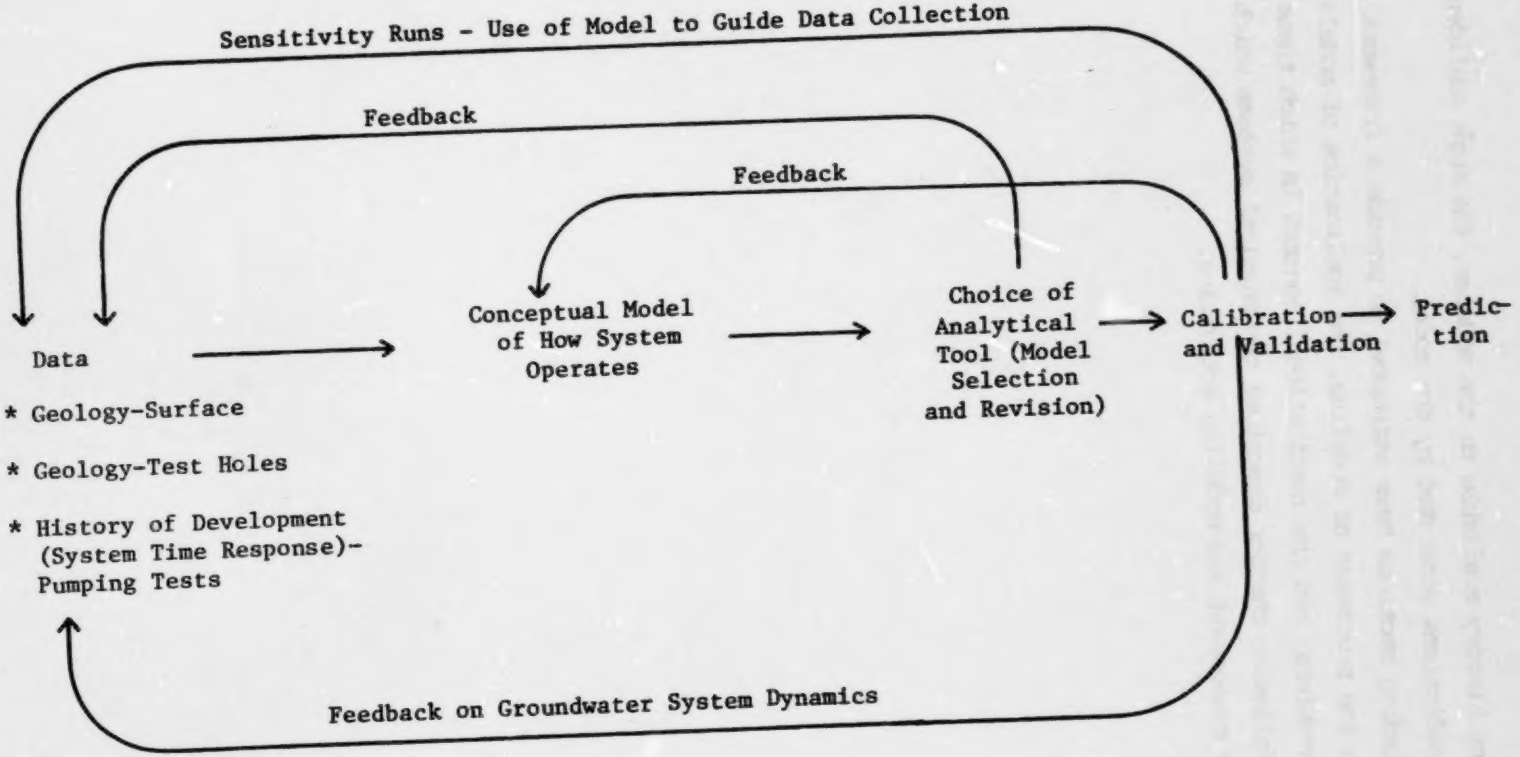

Sensitivity Runs - Use of Model to Guide Data Collection
Feedback
Feedback
Data
* Geology-Surface
* Geology-Test Holes
* History of Development (System Time Response)-Pumping Tests
Conceptual Model of How System Operates
Choice of Analytical Tool (Model Selection and Revision)
Calibration and Validation
Prediction
Feedback on Groundwater System Dynamics

Figure 4. MODELING A REAL SYSTEM (APPLYING THE COMPUTER CODE)

or development history available to the modeler, the more confidence one has in the predictions generated by the model.

The preceding sections have attempted to provide a framework for understanding the processes of modeling, the application of models to groundwater problems, and the institutional context in which these occur. The following chapter describes the physical systems which are the object of management and modeling activities.

# CHAPTER 5

# THE GROUNDWATER SYSTEM AND GROUNDWATER MODELS

Before the technical description of existing groundwater models is presented in the next chapter, it is instructive to review the basic characteristics of the groundwater system itself. The review should help the nontechnical reader to gain a better understanding of the physical entities and processes which apply to groundwater systems and to familiarize himself with the most important technical terms used in groundwater hydrology. Figures 5 and 6 present simplified diagrams which should help clarify further the nature of the groundwater system and man's influence upon it. Following this overview, the general types or categories of groundwater models themselves are introduced, along with an explanation of some further technical terms commonly used in discussing models. This chapter should, in sum, enable the reader to perceive more clearly the relation of models to the management of the groundwater system.

## BASIC CHARACTERISTICS OF THE GROUNDWATER SYSTEM

Groundwater is found at various depths below the earth's surface, in a variety of geologic formations which may serve as underground reservoirs. These reservoirs are known as aquifers, and it is toward the description and management of aquifers that all groundwater modeling is ultimately directed. While aquifers are useful to man chiefly because of their ability to store water, it is important to realize that the water in an aquifer is in constant motion. Both the amount of water stored in an aquifer and the rate of flow through the aquifer will be directly related to the kinds of materials of which the aquifer is composed. These materials range from unconsolidated sediments to bedrock, and include gravel, sand, sandstone, and limestone. Thus, aquifers exhibit a variety

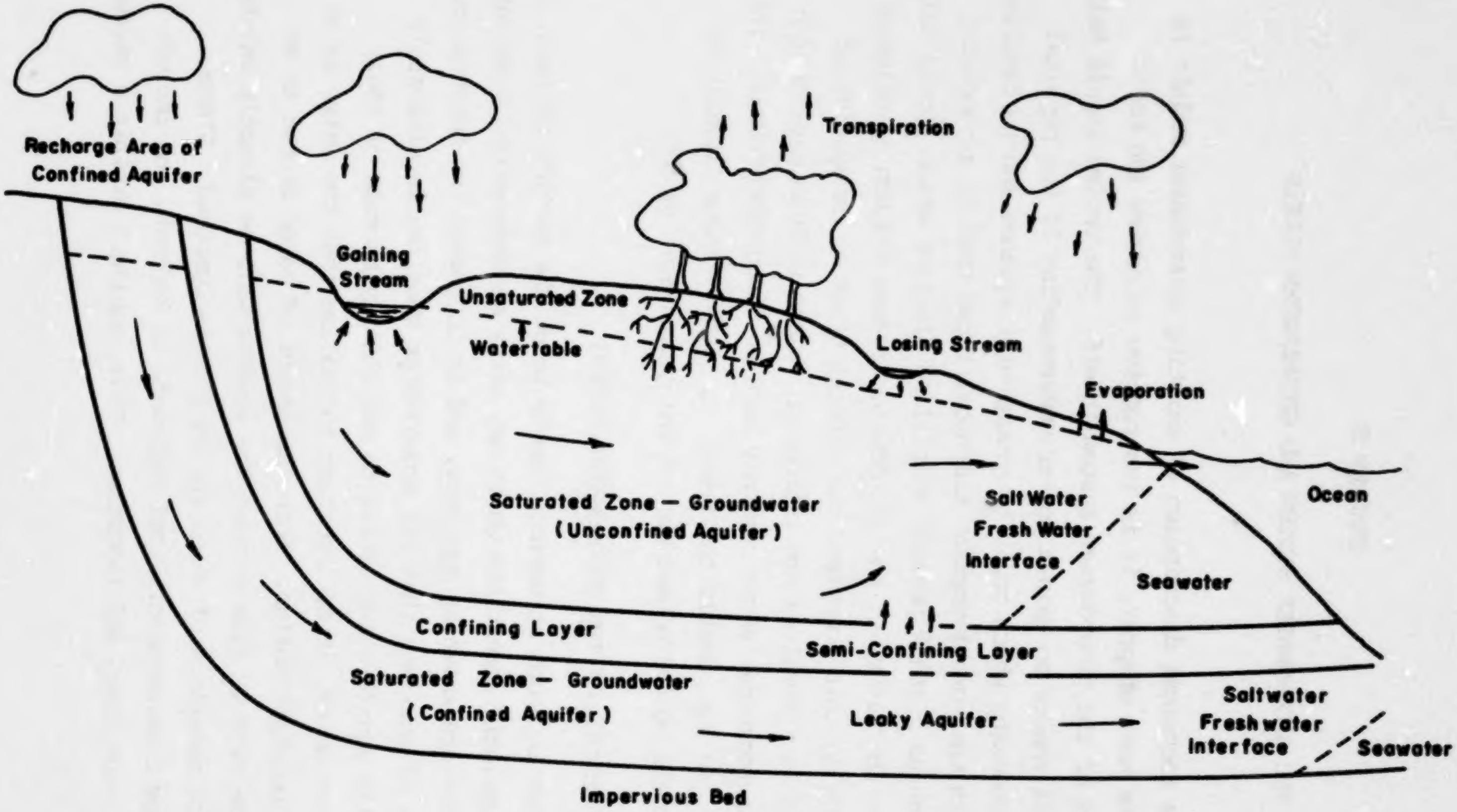
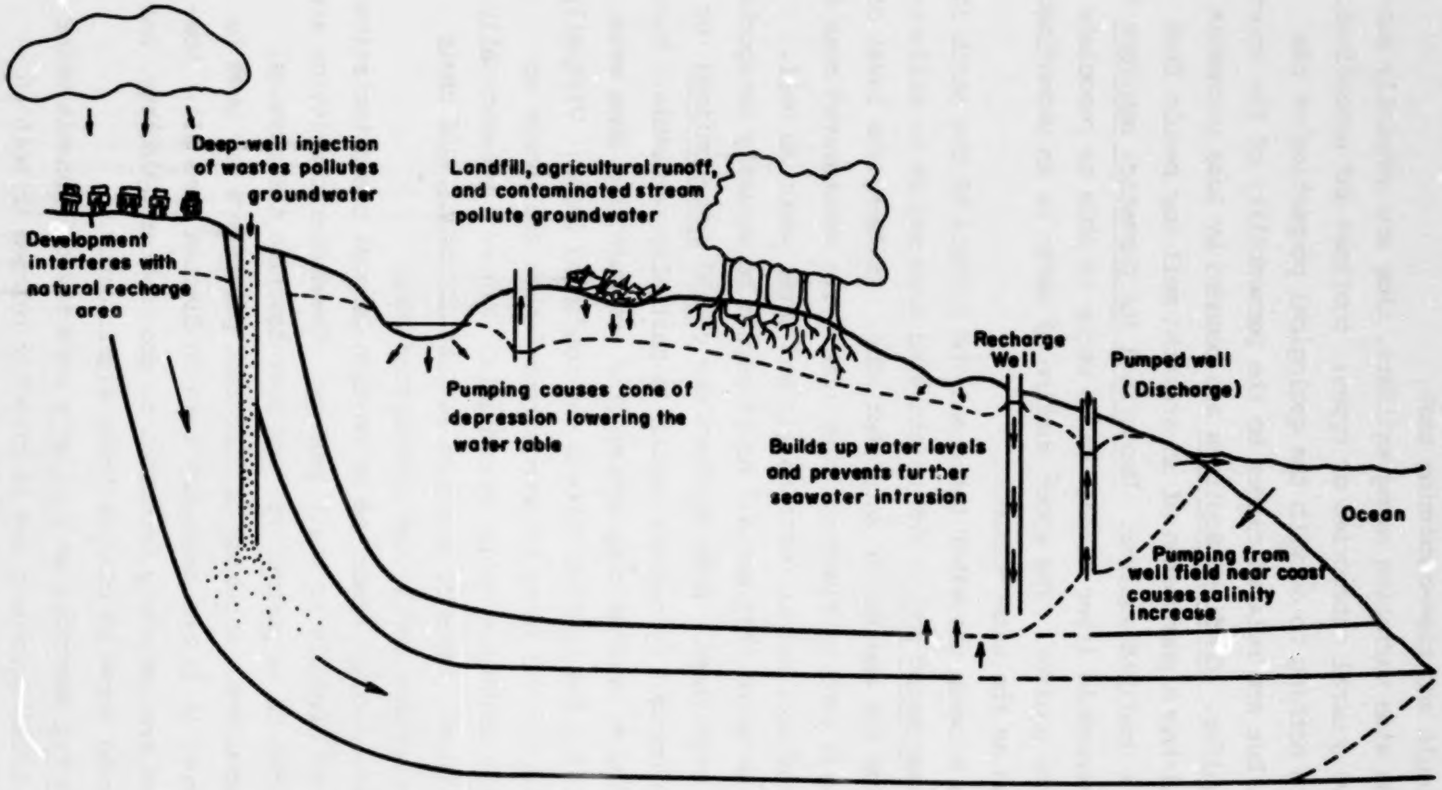

Recharge Area of
Confined Aquifer
Gaining
Stream
Unsaturated Zone
Watertable
Transpiration
Losing Stream
Evaporation
Ocean
Saturated Zone — Groundwater
(Unconfined Aquifer)
Salt Water
Fresh Water
Interface
Seawater
Confining Layer
Semi-Confining Layer
Saturated Zone — Groundwater
(Confined Aquifer)
Leaky Aquifer
Saltwater
Freshwater
Interface
Seawater
Impervious Bed

Figure 5 — The Groundwater System



Deep-well injection of wastes pollutes groundwater
Development interferes with natural recharge area
Landfill, agricultural runoff, and contaminated stream pollute groundwater
Pumping causes cone of depression lowering the water table
Recharge Well
Pumped well (Discharge)
Builds up water levels and prevents further seawater intrusion
Ocean
Pumping from well field near coast causes salinity increase

Figure 6 — MAN'S INFLUENCE ON THE GROUNDWATER SYSTEM

of characteristics and conditions which render the description of any one aquifer a difficult and time-consuming task.

Despite the wide variation among aquifers, they are generally subdivided into two general categories or types: confined and unconfined. These terms have nothing to do with the geological properties of the aquifer itself, but are related rather to the permeability of the strata bounding the aquifer. Confined aquifers are bounded by less permeable rocks. The well-known phenomenon of an artesian well may result from the tapping of a confined aquifer. Unconfined (or phreatic) aquifers are overlain by a permeable layer through which water is able to percolate downward into the aquifer. The upper surface of water in an unconfined aquifer is known as the water table.

The region between the water table and the surface of the earth is known as the unsaturated zone. The unsaturated zone may be no different geologically from the aquifer or saturated zone. In fact, the level of a water table will tend to fluctuate over time. The unsaturated zone does contain some moisture, but it contains air and water vapor as well.

It should be noted that not all aquifers can be strictly categorized as confined or unconfined. Some aquifers are called semi-confined or "leaky" and are bounded by material which is partially permeable. Such aquifers are held at greater than atmospheric pressure, but some water does enter or leave the aquifer through the confining layer. Virtually all confining layers are leaky to some extent; there are almost no natural materials which are truly impermeable. Figure 5 schematically depicts the different types of aquifers as just discussed, and their relation to one another and to the unsaturated zone.

Aquifers are further described by certain general characteristics which are related directly to their geology. These characteristics are normally referred to as parameters, and they describe the physical properties of aquifers. A number of different parameters are used to describe aquifers; it is not necessary here to discuss them all. However, parameters are extremely important to groundwater hydrology, and one example should serve to clarify their significance.

Transmissivity describes an aquifer's capacity to transmit water throughout its total thickness and is directly related to both an aquifer's thickness and its ability to conduct water. Thus, the transmissivity of an aquifer has a great influence on the amount of water potentially available from the aquifer.

Beyond the determination of aquifer parameters, the analysis of groundwater systems also requires the establishment of boundary conditions, which are critical factors in determining how a groundwater system functions naturally and responds to development or other outside influences, stresses. Boundary conditions depend upon the configuration and hydrologic conditions at permeable or semi-pervious boundaries, surface water bodies, and other free surfaces. For the groundwater modeler or technical expert, the identification and assignment of appropriate boundary conditions is instrumental in selecting the proper model which provides an approximate description of the aquifer for analytical purposes.

The foregoing discussion of the groundwater system should make it evident that, strictly speaking, groundwater management involves the movement and storage of water in aquifers. However, the groundwater system is not an isolated entity, and groundwater management must thus be concerned with the hydrologic interconnections between water in the ground and water at the earth's surface. In essence, ground and surface water are interrelated through two processes: recharge and discharge. There are two major sources of natural recharge to an aquifer. The first of these is precipitation which percolates through the unsaturated zone to the aquifer. The second is freshwater inflow from surface water bodies such as streams, rivers and lakes. Natural discharge from an aquifer may occur through several possible outlets. Among these are springs, streams, rivers, lakes, and the ocean. Discharge also occurs through evaporation and through transpiration from plants known as phreatophytes whose roots extend to the water table. Under natural conditions natural recharge and discharge are commonly in balance.

The processes of recharge and discharge intimately link the groundwater system with the rest of the hydrologic cycle, and consequently, the groundwater system can be accurately described as dynamic. Within the aquifer itself, the dynamics of the system revolve around the process of flow, or the movement of water through the porous medium of the aquifer.

In general, groundwater moves under the influence of gravity and pressure in the direction of declining head which is measured in terms of water levels in wells. The specific rate and direction of water movement in an aquifer can be expressed by a set of equations. Rates of groundwater flow are typically in the range of meters per day or year and are far lower than normal rates of surface water flow which are in the range of meters per second. However, the wide variety of conditions present in aquifers inevitably entails a corresponding wide variation in groundwater flow rates.

## MAN'S EFFECT ON THE GROUNDWATER SYSTEM

The dynamic processes of the groundwater system are not only relatively complex natural phenomena which challenge scientific understanding; they are also significantly affected by the activities of man. One of man's greatest impacts on the groundwater system is through the pumping of water from wells which constitute a major source of artificial discharge from the aquifer. The immediate effect of pumping is to lower the head in the immediate vicinity of the well and to produce drawdown in the form of a cone of depression around the well. Major pumping developments thus commonly disturb the balance of inflow and outflow in an aquifer.

As noted in Chapter 4, if groundwater is continuously removed at a rate which exceeds the net recharge (recharge minus natural discharge), a situation of groundwater mining prevails. Mining of groundwater is a common situation in most regions undergoing development and must ultimately deplete the resource unless the water can be replenished through artificial recharge.

Besides withdrawing water from the groundwater system, man may also add materials, usually pollutants, to the system. The common sources of groundwater pollution are illustrated in Figure 6. The range of problems associated with inadequate distribution of pumpage, over-exploitation of an aquifer, and the pollution of groundwater have already been presented in Chapter 4.

## MODELS RELATED TO THE GROUNDWATER SYSTEM

Man's extensive and varied interference with the groundwater systems, as well as the complexities which characterize the response of the groundwater system to that interference, have fostered the development of mathematical tools to aid in the analysis of groundwater conditions and predicting system response. At the simplest level, these mathematical tools include analytical methods, "models", which deal with idealized aquifers assumed to exhibit uniform parameters, simple flow, and regular geometrical boundaries. Analytical solutions to groundwater problems can be carried out with the aid of paper and pencil and perhaps a calculator and generally do not require expensive hardware such as computers. More recently, numerical integration methods have broadened the range of the analytical methods.

For more complex aquifer situations the use of more sophisticated techniques and technology is necessary. Historically, the first such technique to be developed was the analog model. For example, analogues which have been employed for the analysis of groundwater systems include the flow of viscous fluids between plates, or the passage of electrical currents through resistance-capacitance networks.

While the introduction of analog models enabled the analysis of more complex groundwater problems, they generally required a large centralized facility with a large investment in hardware. With the widespread availability of digital computers, analog models have been largely replaced by numerical models which depend on the solution of algebraic equations on the digital computer. Numerical models are capable of analyzing more complex situations with greater ease than the analog models. In addition, numerical models have proved to be far more versatile than their predecessors. Research in the late 1960s produced hybrid models which attempted to combine the best features of the digital computer with the visual display and immediate outputs of the analog model. Hybrid models have not, however, been widely used largely because they have not kept pace with the rapid advances in digital technology.

Among the numerical groundwater models -- the focus of this assessment study -- models with four different major purposes can be distinguished.

These are: 1) prediction models, which simulate the behavior of the groundwater system and its response to stress; 2) resource management models, which integrate prediction with explicit water management decision procedures; 3) identification models, which determine input parameters for both of the above; 4) data manipulation and storage procedures which process and manage input data for all the above.

## Prediction Models

Most of the models produced to date are prediction models which may be subdivided into four major categories: flow, subsidence, mass transport and heat transport.

Flow models utilize information on aquifer parameters, boundary conditions, and man-induced development, to solve mathematical equations for determining quantitative aspects of groundwater flow such as direction and rate of flow, changes in water level, stream-aquifer interactions and interference effects of wells. While most of these models simulate flow in aquifers, flow models have also been developed for the unsaturated zone, and for coupled saturated-unsaturated-surface systems. Flow models are the most commonly used, as well as, the best developed of the groundwater models.

Subsidence or deformation models describe the phenomenon of land subsidence which is caused by withdrawals of groundwater. Subsidence models are needed to predict deformation-related impacts of various pumping schemes in affected areas.

Mass transport models deal primarily with questions of groundwater quality. They are used to predict the movement and concentration in the aquifer of various pollutants including radionuclides, leached solids from landfills and irrigated areas, and salt water intruding in coastal areas. To accomplish this, the models incorporate mathematical approximations of the transport, by means of fluid flow (convection), and/or mixing of one or more chemical constitutents in the groundwater. Because of these considerations, mass transport models in general tend to be more complicated than flow models. Transport models that describe the movement of pollutants without reactions are called conservative; models that also take into account reactions are termed nonconservative.

The oil industry has been active in developing transport models for immiscible substances, oil and water.

Heat transport models couple the flow of heat with water or steam for problems where thermal effects are important. In practice these models have been applied to problems associated with hot springs, geothermal reservoirs and heat storage.

## Resource Management Models

Management models have been developed in an attempt to indicate courses of action which will be consistent with stated management objectives and constraints. The objectives may be, for example, to maximize net economic benefits, to minimize costs, or to ensure adequate water supply at all times for all users. Management models may employ the techniques of both simulation and optimization in deriving their outputs. In contrast to purely physically-based prediction models, management models incorporate economic, technological, political and institutional aspects of the problem being analyzed.

## Identification Models

Parameter identification models have been developed in response to the need to provide improved estimates of parameters. Although engineering techniques have long existed for calculating parameters through pump tests, the identification of parameters for regional groundwater systems must be augmented by regular observations of wells throughout the regional system. As a result, parameter identification models are being developed which attempt to derive parameter values for regional groundwater models through the analysis of long-term historical data.

The task of an identification model can be defined as one of solving a problem which is the inverse of that of prediction, namely: given the historical input to a real system and given a model for predicting its performance, find those parameter values of the model which ensure that the predicted output is as close to the observed one as possible.

## Data Manipulation Codes

The difficulties involved in estimating parameters are closely linked with the more general issue of data collection for groundwater models. As noted in the preceding chapter, while models can be run with any amount of available data, the actual amount and quality of these data directly affect the reliability of the model's results. The task of collecting appropriate amounts of accurate data to ensure model reliability thus implies the need for a fourth class computer code -- data manipulation. These codes can be used in various ways, including specifying data collection procedures, designing data collection networks, identifying critical data, and storing and processing data for use in other models.

## Additional Comments

Related to all of the models treated above is the question of the reliability of model outputs. The factors which affect the reliability of prediction are generally uncertainties about equations, parameters and data used to describe the groundwater system. Uncertainties in some data may be caused by unpredictable future events such as rainfall, demand for water or prices of water. Groundwater modelers are currently divided over the level of effort which should be devoted to incorporating uncertainty in inputs into their models. Ways of incorporating parameter uncertainties into prediction models are being investigated actively at the present time.

The four major classes of groundwater models -- prediction, resource management, identification, and data manipulation -- have been introduced along with their key characteristics in relatively nontechnical language in this chapter. This material should be sufficient for understanding the overview of existing models which is presented in the next chapter along with project findings which are presented in Chapter 7.

# CHAPTER 6

# OVERVIEW OF EXISTING MODELS

## INTRODUCTION

One of the major tasks of this project was to conduct a survey of numerical models related to groundwater management, to provide a basis for identifying future needs in model development and use. The present chapter presents an overview of the results of this survey. It is based primarily on 250 model reports collected from 14 countries as outlined in the following Table.

While reports collected do not provide a complete inventory of the existing numerical models which are related to groundwater management, they probably represent a large percentage of the models currently available, perhaps as large as 80 percent of the total population. It is apparent that the major effort in numerical modeling is concentrated in a relatively small number of developed countries. This, however, does not reflect the geographical scope of application of these models, which is much larger. Indeed, developing countries in various parts of the world benefit from the models through the professional services rendered to them by international organizations (e.g., FAO, UNDP, World Bank) as well as by private and/or government firms which are involved as consultants in water projects around the world.

As indicated earlier, the model reports were presented in the form of responses to a relatively detailed questionnaire concerning the identification of the model and the modeler, the purpose of the model, the conceptual and mathematical framework, the computer code and its applications, and an evaluation of the model based on the modeler's experience.

Two hundred thirty-four of the reports have been forwarded by the modelers themselves. The remaining 16 model reports are based on a review

TABLE 1. SUMMARY OF COLLECTED MODEL REPORTS

| Country | Number of Model Reports | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Prediction | | | | | | | |
| | Total | Flow | Mass Transport | Heat Transport | Deformation | Other | Identification | Management | Data Manipulation |
| U.S. | 112 | 44 | 22 | 5 | 4 | 5 | 9 | 21 | 2 |
| France | 47 | 31 | 5 | 4 | | 1 | 1 | 4 | 1 |
| Israel | 21 | 7 | 7 | | | | 2 | 4 | 1 |
| U.K. | 21 | 18 | 2 | | | | 1 | | |
| Netherlands | 13 | 12 | | | 1 | | | | |
| Canada | 11 | 8 | 2 | | | | 1 | | |
| West Germany | 6 | 4 | 1 | | | | 1 | | |
| Japan | 5 | 2 | | | 3 | | | | |
| Australia | 5 | 5 | | | | | | | |
| Argentina | 5 | 3 | | | | | 1 | | 1 |
| Spain | 1 | 1 | | | | | | | |
| Belgium | 1 | 1 | | | | | | | |
| New Zealand | 1 | 1 | | | | | | | |
| India | 1 | 1 | | | | | | | |
| Total | 250 | 138 | 39 | 9 | 8 | 6 | 16 | 29 | 5 |

of the literature of management models for the past three years prepared by Y. Haimes and P. Das.

## MODEL CHARACTERISTICS

An overview of the surveyed models can, in principle, be based on a variety of model characteristics. However, for the convenience of the reader, this chapter considers only those characteristics which are of common interest to all groups involved, namely managers, model users and model builders. These characteristics include the purpose of the model in terms of the categories described above; the water system treated, whether groundwater alone, or groundwater and surface water; the level of spatial detail (lumped or distributed type models), and the management task which the model addresses. The management tasks have been grouped in accordance with three of the problems outlined in Chapter 4, namely, water supply (quantity); contamination (quality); and environmental impact.

The surveyed models are also reviewed in terms of their accessibility including documentation, availability to potential users and past applications. In this context a model is defined as useable if it is fully documented, available and has been applied to a field case once or more.

Further details on the surveyed models which may be of interest to technical experts and/or modelers are presented in Appendix A.

## GENERAL COMMENTS

Table 2 summarizes the surveyed models in terms of the characteristics described above. A relatively large number of groundwater models address various types of water supply (quantity) problems. A smaller, yet still sizable number of models exists for predicting contaminant levels and the temperature of groundwater (quality). The environmental impact of land subsidence is covered by several models, whereas ecosystem impacts have not been reported.

Only a few models have been developed for coupled groundwater-surface water systems. Of these the majority are management models, with the remainder treating flow and mass transport.

Only a few of the surveyed models consider uncertainties in an effort to provide an estimate of possible error in the output. Similarly,

## TABLE 2. OVERVIEW OF SURVEYED MODELS

| Model Category | Number of Reports | Groundwater |  |  |  |  | Groundwater & Surface Water |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | Quantity |  | Quality |  | Environmental Impact | Quantity |  | Quality |  | Environmental Impact |
|  |  | Lumped | Distributed | Lumped | Distributed |  | Lumped | Distributed | Lumped | Distributed |  |
| Prediction |  |  |  |  |  |  |  |  |  |  |  |
| Flow |  |  |  |  |  |  |  |  |  |  |  |
| Water | 127 | 2 | 119[**b] |  | 2[*e] |  |  | 4[*] |  |  |  |
| Water & other fluids | 11 |  | 5[*] |  | 6[e] |  |  |  |  |  |  |
| Mass transport |  |  |  |  |  |  |  |  |  |  |  |
| Conservative | 20 |  |  | 2[a] | 17[**f] |  |  |  | 1[*a] |  |  |
| Nonconservative | 19 |  |  | 2[*] | 17[**d] |  |  |  |  |  |  |
| Heat transport | 9 |  |  |  | 9[*c] |  |  |  |  |  |  |
| Deformation | 8 |  |  |  |  | 8 |  |  |  |  |  |
| Others | 6[g] |  |  |  |  |  |  |  |  |  |  |
| Management | 29 |  | 10[*] |  | 3[a] |  | 7 | 6[*] | 2 | 1 |  |
| Identification | 16 | 2 | 14[*] |  |  |  |  |  |  |  |  |
| Data manipulation | 5 |  |  |  |  |  |  |  |  |  |  |
| Total | 250 |  |  |  |  |  |  |  |  |  |  |

[*] One "usable" model in group.

[**] Two or more "usable" models in group.

[a] Treats waste disposal and reclamation.

[b] Sixteen models treat coupled saturated-unsaturated systems.

[c] Treats thermal problems 2 of which are geothermal.

[d] Two models treat biochemical reactions.

[e] Treats interface.

[f] Two models treat interface.

[g] Includes 1 frost propagation, 1 coupled heat-mass transport, 2 coupled subsidence and heat transport models and 1 general purpose code.

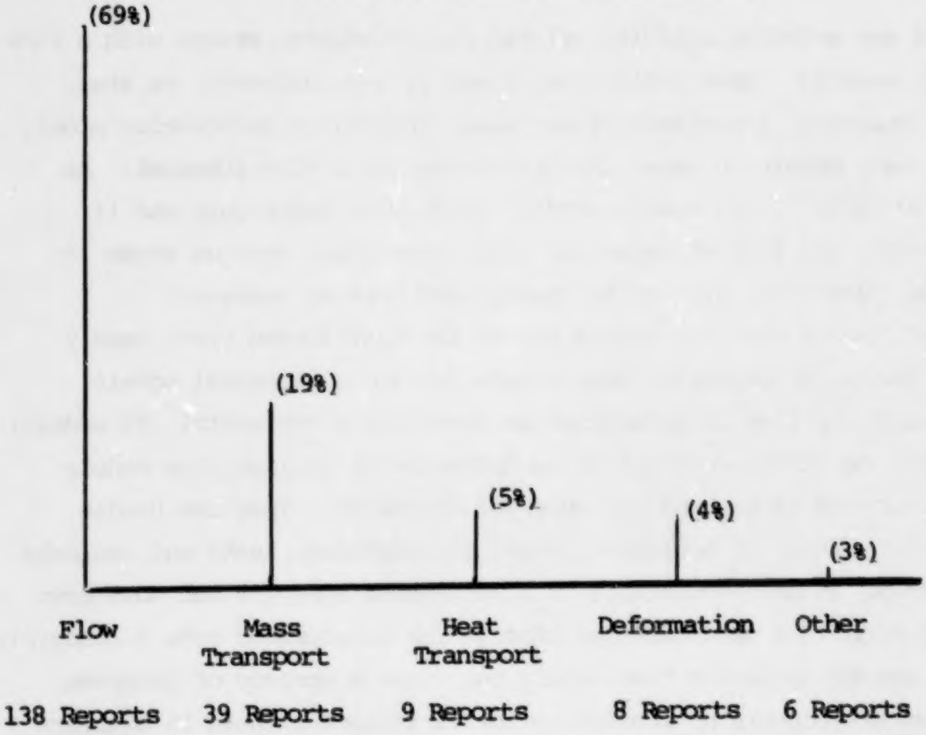
only 12 percent of the models surveyed can be classed as useable. Out of 250 surveyed models only 30 have been completely documented, are available and have been applied at least once to a field case, and only 13 of these treat problems other than groundwater flow. This situation seems to result from restrictions on availability of codes developed by private and semipublic agencies, poor documentation of codes developed at universities, and difficulties in applying existing codes to field problems.

The following sections review each category separately.

## PREDICTION MODELS

Prediction models constitute nearly 80 percent of the surveyed models (199 out of 250). The purpose of prediction models is to forecast spatial and temporal changes in the movement of water, contaminants, heat and land. The following diagram shows the distribution of these models.

Distribution of Prediction Models



A common feature of all prediction models is that their forecasts are deterministic (one value) rather than probabilistic (a range of values of varying probability). In most cases the predictions are also unconditional, implying that the models do not contain any restrictions on acceptable values or operations. However, some of the prediction models have provisions for including operating rules as well as constraints on water levels, water quantity and/or quality. Such models are useful in predicting effects of alternative policies of groundwater-related management of water resources.

Some prediction models, especially flow models, contain nonhydrologic elements such as crop production, and thus can be used to assess the hydrologic effects of nonhydrologic activities and vice versa. Such prediction models are also used in conjunction with optimization routines in management models.

## Flow Models

Almost any modeling activity related to groundwater starts with a flow model. For example, since quality and quantity are intimately related, flow is an essential ingredient of any water quality or deformation model. Therefore, many models in other categories contain a flow submodel. As indicated in Table 2, 127 models handle the flow of water only and 11 models consider the flow of water and some other fluid such as steam in a geothermal reservoir, air in the unsaturated zone or seawater.

All but two of the flow models are of the distributed type, namely they have spatial components. Most common are two-dimensional models which consider the flow in an aquifer as essentially horizontal (95 models). These models, sometimes referred to as hydraulic or aquifer flow models have been reported by each of the surveyed countries. They can handle flow in various kinds of aquifers: phreatic, confined, leaky and nonleaky. Twenty of them can handle multiple or multilayered aquifers and some even contain a submodel of vertical flow through the unsaturated zone (5 models).

The surveyed hydraulic flow models can serve a variety of purposes. Most of them are capable of predicting the variations in head in aquifers and evaluating rates of water flow under differing patterns of recharge and withdrawal. Some also serve special purposes such as predicting the amount of flow between aquifers and streams (19 models), determining the flow pattern or the location of boundaries between native and injected water bodies as well as travel times of water particles (9 models), predicting the movement of the interface between fresh and salt water (8 models), and determining spring flow, water levels in wells, evapotranspiration and others (5 models). In general, most of these models have been applied to solving field problems and many of their codes have been sufficiently well documented and are flexible enough to be utilized by others.

Less frequent are the 29 models which are three-dimensional or two-dimensional in the vertical plane which can predict head in an aquifer as a function of depth. These models are capable of taking into account the depth of penetration of wells and the configuration of boundaries. They are powerful in determining flow patterns around wells and surface water bodies as well as the configuration of the water table in phreatic aquifers. They can also be used in making a first order evaluation of the spread of contaminants from disposal or recharge sites or the concentration of such contaminants in wells on the basis of the flow pattern only. Some of these models have been applied to field studies and are available.

A few one-dimensional flow models have been used to study flow from aquifers toward rivers or oceans with approximately straight shorelines. Some of the freshwater-seawater interface models as well as one of the groundwater-surface water flow models are of this kind.

Some of the limitations and deficiencies of the surveyed flow models are worth noting. In contrast to the relatively large number and variety of models which can handle flow in aquifers and in the unsaturated zone, only four models have been surveyed which can handle both groundwater and surface water. The surveyed flow models do not explicity handle flow in aquifers dominated by fractures, joints or solutions caverns. Neither do they handle moving boundaries. The major technical difficulties reported by modelers were obtaining numerical solutions in the case of drastically varying flow conditions, and trying to find an appropriate compromise between the desired level of model accuracy and the amount of data and computer capacity available.

## Mass Transport Models

As indicated in Table 2, the number of surveyed mass transport models, 39, is much smaller than that of the flow models, 138. Whereas, flow models were reported by all fourteen countries which have been surveyed, mass transport models came from six countries only, mostly from the United States. Also, while flow models were usually the work of one individual, the surveyed mass transport models have in at least half of the cases been developed by a team of two or more. All of the reported models have been developed during the last five years and many of them are still undergoing improvements.

Mass Transport models are more complex than flow models in that they consider quality in conjunction with quantity. In principle, a mass transport model contains a flow submodel which computes the flow velocity of the water and thus utilizes these velocities in a quality submodel which transports the contaminant in the flow field allowing for additional spreading (dispersion) and transformations by reactions. Under certain circumstances such as low concentrations of contaminants, flow and quality submodels can operate independently. In other cases, however, their mutual effects cannot be separated. Thus, relatively high contaminant concentrations in wastewater or saltwater affect the flow pattern of the groundwater which in turn affects the movement and spreading of the contaminants, this requires a more intimate interactive coupling between the flow and quality submodels. Only two of the surveyed models have fully coupled flow and quality submodels which account for the effects of varying density upon the flow field.

As indicated in Table 2, there are almost equal numbers of mass transport models which consider contaminant transport by flow only (conservative mass transport) and those which consider reactions as well (non-conservative mass transport). The latter include primarily adsorption and radioactive decay, the mathematics of which is relatively easy. Some of the multiconstituent models also consider chemical reactions under simplified assumptions. However, only two of these models handle the more complicated biochemical transformations of nitrogen compounds which are important in modeling the effects of contamination by organic waste products and the efficiency of waste treatment.

The desired level of detail of a mass transport model is of major importance in water quality planning. Thus, lumped mass transport models which may consider a large portion of an aquifer as a single unit can be useful in predicting long term regionwide trends of contamination from surface sources or by geochemical processes. Unfortunately, only five such models have been reported. Most of the surveyed mass transport models are of the distributed type, 22 models of which predict concentration of contaminants in the saturated zone, 7 in the unsaturated zone, and 5 in both zones. About half of the distributed models handle two-dimensional horizontal mass transport, one quarter can handle more complicated geometries, and one quarter are one-dimensional.

Several difficulties impair both the credibility and the efficient use of mass transport models. A technical difficulty is "numerical dispersion" in which the actual physical dispersing mechanisms of the contaminant becomes negligible in comparison to that caused by the computational scheme. A conceptual difficulty is that of incorporating the effect of the unsaturated zone on the concentration and arrival time of contaminants reaching the groundwater. The heterogeneity of this zone, and the complex transformations undergone by contaminants in this soil-plant-water-air environment contribute to this difficulty.

There are also difficulties with water quality predictions in the saturated zone. Typically, horizontal mass transport models are used in conjunction with hydraulic aquifer flow models. However, these models tend to underestimate peak values and thus may fail to predict dangerous concentration levels in the neighborhood of surface sources of contaminations and critical arrival times of pollutants in wells. Density differences between heavy wastewater and lighter groundwater which may enhance the propagation of pollutants in the neighborhood of large scale waste disposal sites and the bacteriological aspects of contaminations have not as yet been adequately treated.

Finally, there are difficulties related to computer capacity and data requirements. While there are relatively simple and inexpensive field methods for determining parameters for flow models, no such comparable methods have as yet been developed for mass transport models.

In conclusion, it is fair to say that the existing mass transport models are adequate for obtaining first order estimates of contaminant movement.

## Heat Transport Models

The temperature of groundwater is usually of lesser importance to the water resource manager than its chemical or bacteriological quality. However, heat transport models have recently grown in importance as underground storage of heat, thermal pollution as an environmental factor, and exploitation of geothermal energy have become more common.

Heat transport models are conceptually similar to mass transport models in that a flow submodel is coupled with a heat flow submodel which incorporates various mechanisms of heat transfer. The problems faced by heat transport models are similar to those discussed for mass transport models.

Only nine heat transport models were reported in this survey, five of which have been recently completed. All of the reported models are of the distributed type, and all but one deal with the saturated zone. Three of the models predict the temperature in wells and have been applied primarily to feasibility studies of heat storage. More recent models consider coupled flow and heat transport. Two of them handle temperature as well as vertical or horizontal flow of water and steam in geothermal reservoirs, one is concerned with the effect of temperature on evaporation losses, and the remaining three are multipurpose three-dimensional models. To summarize, at present, for heat transport models, field application significantly lags model development. There are only a handful of places around the world where data sufficiently adequate to provide field validation of the available models have been collected.

## Deformation Models

Unlike the previous models which predict water quantity and quality, the surveyed deformation models are concerned with the effect of pumpage or recharge on the deformation of the land surface. Usually the land surface deformation is computed on the basis of the change in head or pressure obtained from a flow submodel under various assumptions regarding the relationship between the change in pressure and the deformation of the aquifer.

Eight deformation models have been surveyed in this study. Six of them predict subsidence or uplift, two also predict lateral displacements. Four of those predicting subsidence use a hydraulic flow model coupled with a linear deformation submodel. These models operate with easily accessible flow parameters and have had many field applications. The other four models are more detailed and complicated and it is unlikely that they will be applied to actual field problems in the foreseeable future.

### Other Prediction Models

Recently attempts have been made to standardize computational techniques for prediction models and to broaden the scope of their capabilities. Six models of this kind have been reported. They include two general purpose computer codes for flow and transport phenomena, a code for predicting frost propagation used in the design of roads, two coupled heat and deformation codes for predicting pressure and temperature in accumulating sediments or in a geothermal reservoir, and one coupled heat and mass transport code for predicting pressure, contaminant concentrations and temperature in an aquifer.

## MANAGEMENT MODELS

All of the surveyed management models deal primarily with engineering decisions and a single economic or physical objective. Management models are conceptually more complex than prediction models because they contain additional aspects of decision making. This introduces more submodels and data, as well as additional computation.

Usually a management model contains four elements: a submodel for finding the most appropriate decisions (e.g., location of wells, pumping rates); a submodel for predicting the outcome of a decision (e.g., water levels, salinity); a set of rules and constraints on admissible decisions and/or outcomes (e.g., maximum pumping rates, drawdowns, salinity, water rights, well regulations); and a so-called objective function which evaluates a decision (e.g., cost, benefit, yield).

Twenty-nine management models have been surveyed in the course of this study. Fifteen of them have been reported by the modelers themselves, whereas fourteen are based on a review of the water resource management literature over the past three years.

## Groundwater Alone

As Table 2 indicates, models exist for the management of quantity and quality of either groundwater alone or of both groundwater and surface water. All of the groundwater management models are of the distributed type and most of them deal with the management of water quality in a single aquifer containing a well field. Usually the objective is to distribute the pumpage so as to satisfy a given demand at minimum cost or to maximize benefits from the use of the pumped water. Other models address decisions for agricultural production, fiscal policies to encourage efficient basinwide use of groundwater, and cost-benefit evaluation of collecting additional data.

Only three of the surveyed models deal with the management of groundwater quality. One of them couples groundwater allocation for irrigation with salinity control while attempting to maximize the net benefit associated with water use. The other two consider wastewater disposal through wells in conjunction with groundwater supply and surface treatment of wastewater. Unfortunately, only a few of the above models have been applied to actual management tasks and only one of those is documented and available for use.

## Groundwater and Surface Water

The conjunctive groundwater-surface water management models are distinct in considering a variety of multicomponent systems such as resources, supply use, production, and in addressing management tasks at a regional level. Most of them deal with quantity management and at two levels of detail: lumped and distributed. One of the lumped models seeks to optimize the price of water, taking into consideration the relationship between demand, supply, and price. Other lumped models seek to optimize development and operation while either maximizing expected benefits or minimizing costs. Two of the lumped regional quantity management models are actually used for regional management of water resources in Israel.

Some of the distributed quantity management models are distinct in treating stream-aquifer interactions and in addressing coordinated multilevel management. The latter is a recently developed methodology which can serve the needs of decentralized water resource management. By this methodology, several independent agencies which administer different parts of a regional water resources system can enjoy the benefit of coordinating their activities so as to best utilize the limited water resources of the region. Another advantage of this methodology is the decomposition of large scale complex water systems into smaller ones, while seeking a regionally optimal scheme of operations and/or development. One such multilevel management model is useable.

Finally, quality management of a groundwater-surface water system is handled by three of the surveyed models. Two lumped models determine an optimal pattern of pumpage, of wastewater treatment and of resource allocation so as to meet a desired quantity and quality of the supplied water at a given reliability level. The third model is distributed and aims at operating available local surface and groundwater resources in conjunction with water importation so as to satisfy agricultural water demand in terms of quality and salinity at minimum cost.

In conclusion, it is fair to say that so far the contribution of the management models has been primarily in the area of research and development. Regardless of whether a water resources management system is centralized or decentralized, it is obvious that existing management models can in certain cases be useful in enhancing management practices and in screening decision alternatives. The application of existing management models to real problems will foster the development of better techniques to address multiple objectives and nonengineering decisions.

## IDENTIFICATION MODELS

An adequate estimation of parameters is probably the major stumbling block to efficiently utilizing the already available prediction and management codes. Much current modeling effort is directed towards developing calibration techniques which are both conceptually sound and computationally efficient.

All of the sixteen identification codes which have been surveyed estimate parameters related to groundwater quantity only, primarily for distributed horizontal flow models. Unfortunately, only one of the surveyed models is both domumented and available. Ten, however, have been applied to field data at least once.

Two methods of calibration are commonly used. For the indirect approach, a succession of model outputs is used to successively improve parameter values. For the direct approach parameter values are computed from the given input and output data without utilizing a succession of model runs. Both approaches have been widely applied and most of the surveyed models find the best values of parameters by optimization techniques. A few models, however, still employ "trial by error" methods. The direct approach of calibration is attractive as it usually saves computer time and its results do not depend on the initial guess of the parameters. Past difficulties with computer storage requirements for this method seem to have been resolved by using new mathematical techniques.

Two identification models are distinct in deriving response coefficients or functions rather than single parameter values. One of them is a statistical regression model the coefficients of which link drawdown to pumpage, the other one, which transforms aggregated inputs into aggregated outputs is suitable for calibrating lumped parameter prediction models. Finally, one of the distributed identification models yields in addition to parameter estimates their standard error and other statistical characteristics.

Despite the progress made in the development of identification codes, some basic conceptual and methodological questions require further attention. These include the definition of "best" parameter values and the selection of such values. Other issues include the updating of parameter values as new information becomes available and addressing the uniqueness and dynamic character of parameter values. To conclude, although some parameter identification models have been made operational, they have not in general been widely applied to practical problems.

## DATA MANIPULATION

Each of the model categories reviewed utilized data of various kinds such as water levels, contaminant concentrations, pumpage, recharge, and many others. These data, most of which are collected in the field, are commonly placed in primary data files. They are then processed in various ways such as sorting, interpolation, aggregation, and statistical analysis, before being placed in secondary data files for use in the modeling process. Many of these tasks are performed by data manipulation codes. In addition, such codes, with output that may be in the form of tables, contour maps, and plots, are used for producing status reports on groundwater levels and quality in aquifers.

Only five data manipulation codes have been surveyed. Two of them may be of general interest. One handles error detection in groundwater head data, and the other interpolates between point data and assess its error. The remaining three codes deal with the retrieval of data from groundwater data bases and with the preparation of input data to flow models. Many of the models discussed above contain special data manipulation routines for the display of their output.

Of interest is that the United States Geological Survey is operating a national water data storage and retrieval system (WATSTORE). The system is operated and maintained through fifty terminals located in major cities throughout the United States. The system contains, among others, a groundwater file in which can be stored physical, hydrological and geological data. A user's guide for the preparation and submission of groundwater data as well as for the retrieval of such data is in the process of publication. Steps are currently underway to include in WATSTORE data on water use in addition to existing data on water levels and water quality.

## MODEL USABILITY

The survey of the existing models contained questions regarding the state of documentation, availability and past applications of such models.

Although most of the modelers have responded to these questions, some have answered just a part of them and some have ignored them altogether. Table 3 summarizes the collected information.

Documentation. Only 30 percent of the surveyed models have available a description of the model, a listing of its code and a user's manual and thus can be considered as fully documented. The percentage of fully documented models is about the same for the major model categories.

Availability. Only 42 percent of the surveyed models are available to potential users free or at nominal cost. Most of these have been developed at universities and some at state agencies. Models which have been developed and documented by the U.S.G.S. are usually available. Models developed by consulting firms are usually available only as part of their consulting service. Identification models, which are still largely in a research stage of development, are the least available category of models.

Applications. Sixty-eight percent of the surveyed models have been applied to a field case at least once. Models developed and operated by consulting firms as well as state agencies and the U.S.G.S. have usually been applied many times. Most of the models which have not been applied in the field come from universities. The applied prediction models which make up 71 percent of the total, have the greatest rate of field applications; management models, with 41 percent, have the smallest rate.

Usability. A model was earlier defined as useable if it is fully documented, available at no cost, and applied once or more in the field. Only 14 percent of all the surveyed models fall in this category.

## CONCLUDING REMARKS

In principle the existing numerical models are capable of handling most groundwater-related management problems. In practice, however, their successful application to such problems varies from one model category to another.

Water quantity models, and in particular hydraulic aquifer flow models, are operational and widely applied. In contrast, coupled

TABLE 3. STATE OF USABILITY OF THE SURVEYED MODELS

| MODEL CATEGORY | NUMBER OF MODELS | | | | |
|---|---|---|---|---|---|
| | TOTAL | DOCUMENTED | AVAILABLE | APPLIED | USABLE |
| Prediction | | | | | |
| Flow | 138 | 41 | 61 | 106 | 22 |
| Mass Transport | 39 | 11 | 17 | 23 | 3 |
| Heat Transport | 9 | 4 | 4 | 4 | 1 |
| Deformation | 8 | | 2 | 6 | 0 |
| Others | 6 | 3 | 4 | 2 | 2 |
| Management | 29 | 8 | 10 | 12 | 3 |
| Identification | 16 | 5 | 4 | 10 | 3 |
| Data Manipulation | 5 | 3 | 2 | 5 | 1 |
| TOTAL | 250 | 75 | 104 | 169 | 35 |
| Percent | 100 | 30 | 42 | 68 | 14 |

groundwater-surface water flow models are scarce and models of flow in aquifers with secondary porosity such as karst are lacking.

Water quality models, which are more difficult to develop, have been developed in only a few countries. Despite some field applications of distributed water quality models, their utility is lessened by a variety of difficulties. On the other hand, lumped water quality models, which are easier to develop and which could be useful in evaluating long term regional trends, are scarce.

A number of management models have recently been developed which primarily address engineering decisions and a single economic or physical objective. While most of these models have been developed in the United States, only in Israel, and to some extent, France, are management models utilized on a routine basis.

The reliability of prediction and management models would be improved by better parameter estimation. While relatively simple and inexpensive field methods exist for the evaluation of parameters for aquifer flow models, such methods are not available for water quality models. At the same time, regional identification codes need further conceptual and technical improvements before they can become operational.

# CHAPTER 7

# GAPS IN MODEL APPLICATIONS TO MANAGEMENT NEEDS

The previous chapter presents the findings of the project related to the existence and degree of development and application of models for various management problems as they were reported by model developers. The central purpose of this chapter is the presentation of findings related to barriers to the efficient use of such models in groundwater resource management as they are viewed by model users.

## SOURCE OF INFORMATION

The findings contained in this chapter are the result of an intensive effort on the part of the project staff and steering committee to gather information on the needs of managers and the difficulties of technical experts in applying models to management problems. While an attempt was made to address some managers directly, the major portion of this information was obtained from those individuals identified as technical experts. These include persons active in engineering, planning, and consulting.

The technical experts were surveyed extensively by mail through short questionnaires, and more intensively through workshops in the United States and Europe. The workshops involved the discussion of the participant's specific problems, tasks related to those problems, and the kinds of models needed to perform those tasks. The participants were divided into small groups which focused on difficulties both in the available models and in the application of models to management problems. The exchange of opinions during these group sessions proved to be the project's most valuable source of information concerning gaps in modeling and model application.

In addition to the surveys of technical experts, supplementary information on gaps was drawn from a section on evaluation and recommendations which was included in the questionnaire sent to groundwater modelers throughout the world. A more detailed description of the process by which information was collected is to be found in Chapter 3 of this report.

## CATEGORIES OF GAPS

For the purpose of identifying gaps, four major categories have been defined under which the various issues regarding models and their applications have been ordered. The first of these categories, accessibility of models to users, was deemed to be the most serious barrier to the successful use of models to solve management problems. The other categories, in order of importance, are: lack of communications between managers and professional experts, inadequacies of data, and inadequacies in the models.

Under each of the categories a series of topics is discussed. These topics emerged as major concerns of those involved in using models in groundwater resource management. Different groups had diverging opinions of the real nature of the needs of management and the deficiencies of models, and thus the relative importance of the various areas of concern was difficult to evaluate. The following discussion presents consensus where it emerged and, where consensus was not reached, attempts to present the important positions and to attribute these positions to specific groups where possible.

## ACCESSIBILITY OF MODELS TO USERS

Of all the areas of concern identified over the course of the project, difficulties in gaining access to models appeared to be the most serious. Individuals needing models are often not aware of what models are available to them, nor do they know where to turn to find this information. While the project did not reach a clear consensus on priorities, it can be safely stated that all of the factors affecting accessibility which are discussed in the following paragraphs were considered to be of major concern.

## Model Documentation

The lack of adequate documentation of existing models was repeatedly identified in project workshops and questionnaires as a major deficiency. Proper documentation should include a description of the model, a listing of the code, and a user's manual. The first of these provides a brief description of a model's general characteristics, capabilities, and range of possible applications. When such documentation exists, it is typically not written in a consistent format and is scattered throughout the literature. Consequently, potential users often have little information concerning the models which are available. This report, through its catalog of existing numerical groundwater models, should provide a first step toward filling this documentation gap.

Documentation should provide an easy means of running the model on a computer. Unfortunately, a listing of the model's code is not always easily accessible. The documentation should also provide specific technical instructions that may assist in the utilization of the model's code. Unfortunately, a satisfactorily detailed user's manual which would allow a model to be applied by individuals other than the model developer, usually has not been prepared.

A number of reasons have been put forward for the inadequacy of present documentation. The most important among these is that documenting a model is the last step in the modeling process, and is in fact not necessary for the immediate solution of the problem for which a model is built. Typically, most available funds are exhausted in the building of a model, and little money may be left for the preparation of a user's manual. Furthermore, documentation is expensive and time-consuming, and is not readily written by model builders who may have little training or interest in detailed expository writing. Finally, modelers may have insufficient incentive to document since they may be reluctant to expose particular features, uncertainties or assumptions which the models may contain.

It is significant that the quality or extent of model documentation tends to vary with the type of institution in which model development takes place. At present within the United States, the most complete documentation of groundwater models is available from the U.S. Geological

Survey, a federal agency which considers as part of its mission to develop and distribute models for the analysis of field problems. Private consulting firms, on the other hand, develop proprietary models for specific clients and generally do not find it in their interest to distribute their work widely at low cost. The least extensive documentation is developed in the university community where much modeling is commonly undertaken in conjunction with doctoral programs or research grants which generally do not require the preparation of user's manuals.

## Model Distribution

Closely linked to documentation is the distribution of models; a well-documented model must be publicized and distributed to be of any value to prospective users. At present, there is no readily available service for the systematic collection and dissemination of information on models as they become available or as they are applied to different situations. While this project represents a first step toward filling this gap, no provision has been made for continuing a service to model users on a periodic and updated basis. Moreover, information on the existence of a computer code is not enough to make it available to a potential user. Public funds spent on model development are wasted if public agencies in need of such codes have no access to them.

What seems necessary to solve this problem is a central facility or "clearinghouse" which would be responsible not only for the collection of information pertaining to models, but would also engage in an active program of making this information available to users. It is desirable to establish such a center on an international basis. The development of models is expensive; unnecessary duplication of effort as well as international cooperation would be promoted by creating an international information center. Perhaps more importantly, such a center is most needed by those developing nations which have little modeling expertise of their own and limited resources upon which to draw.

An information facility of this nature might be most appropriately lodged in some branch of the United Nations, or it could become the responsibility of some other scientific organizations which is internationally based. If an international center should prove infeasible, such information centers should be encouraged on a national basis. Within the United States any of several agencies of the federal government might be appropriate for this purpose; alternatively a university or non-profit organization could house such a facility. Unfortunately, a number of the potential institutions which might house an information center have been involved in model building; this makes them subject to bias. Whether true or not they would be suspected of promoting their own models. The U.S. Geological Survey, one agency which might house such a service, is reluctant because of its own involvement in model building.

One problem inherent in the idea of a central facility for the collection and distribution of model information is the potential conflict with consulting firms. The precise functions of the facility would have to be carefully considered and defined if it is to complement rather than compete with existing institutions.

## Training of Model Users

Although many project respondents laid strong emphasis on gaps in documentation and distribution, others expressed the view that the closing of these gaps will not make models more accessible. Rather, these actions must be coupled with the training of those professionals who use models. Access to models is often inhibited by limited understanding on the part of technical experts concerning the models that are available, which of those models are best suited to particular problems, and how the appropriate models, once identified, should be applied or modified to fit their needs.

Beyond the consideration of a variety of available models, once a user has chosen a particular model he must understand; 1) its structure, 2) underlying assumptions, and 3) its limits if he is to ensure successful application of the model to the problem under study. Because model builders cannot possibly be involved in all the applications of their models, training of technical personnel for this job is necessary. The lack of field personnel with adequate training in the application of models is due at least in part to the rapid development of modeling in recent years, a process with which many field personnel have not managed to keep up.

Universities have taken steps to improve the education of professionals in the use of models; training programs have been extended to include "short courses" and seminars for those field practitioners who wish to learn more about the applications of models. Such programs, particularly those directed toward field practitioners, should be encouraged and expanded.

Ideally, technical experts trained in the use of models should be part of the management organization which is responsible for solving the problems to which the model is to be applied. In this case there may be the greatest possible incentive for the expert to use the model properly, and there is also a good possibility that the model will be updated and improved. The use of outside consultants may, however, be more reliable and efficient for an agency which finds it difficult or undesirable, especially for financial reasons, to maintain a skilled in-house staff of modelers and related experts.

Within the United States, the U.S. Geological Survey has filled the role of providing centralized groundwater modeling expertise to a variety of public agencies at state and local levels. The scarcity of trained personnel is a more acute problem for the developing world. In fact, the lack of adequate expertise and technical knowledge appears in many cases to be the most serious limiting factor in the distribution and use of models in the Third World.

## COMMUNICATIONS BETWEEN MANAGERS AND TECHNICAL PERSONNEL

Communication issues have consistently emerged as important in improving the utility of models for addressing groundwater management problems. It is far easier to identify communications problems than it is to propose measures for their solution. In fact, such problems cannot, by their very nature be "solved;" they can only be ameliorated. Lack of adequate communications is a widespread source of difficulties in model application and may take many forms. The following test presents a range of topics which have consistently emerged as major themes in discussions of these problems.

## Model Credibility

One of the more common and better publicized factors which has hampered the utility of models in groundwater management, is the lack of confidence on the part of managers in models as decision-making tools. This credibility gap may in some cases be more apparent than real. Managers must respond to a great many political pressures and consequently may have reasons for not wanting to use a model even if they have confidence in its output. In such a situation they might find it easier to ignore the model than to overcome political barriers to its use.

Where credibility is indeed a problem, one of the most important reasons for it may be the fact that groundwater modeling is becoming an increasingly sophisticated science which has developed rapidly in recent years. Many persons currently occupying management positions are thus unfamiliar with modeling techniques and have no feel for the application of models to their particular problems. While managers do not have to be well-versed in the technical details of models in order to accept them, they do need some appreciation of the conceptual framework and the inherent capabilities, limitations, and assumptions of models.

This lack of understanding on the part of management gives rise to what is known among professionals as the "black box" phenomenon. While some managers are willing at the outset to accept practically any model output uncritically, this initial enthusiasm often leads to disappointments and consequent distrust. Often, however, a manager will tend to view models as technological mysteries which operate in unknown and unknowable ways. As a result, a manager may reject models as machines which unnecessarily complicate, and may even threaten his job. Managers may also distrust model outputs that contradict their intuitive preconceptions about the phenomena under study.

A lack of trust in models by managers may, on the other hand, be due to causes other than insufficient understanding. The fault may lie with the professionals who build and apply models. One serious problem of this kind has been the "overselling" of models, whereby modelers have claimed that their models can perform more than is actually possible, or have otherwise misrepresented the true capabilities of models. Closely related to this problem has been the practice of "overmodeling," which is the application of a model which is too sophisticated for the task being performed. Both overselling and overmodeling have led to understandable disillusionment on the part of managers, and to the consequent impression that models do not produce efficient, reliable, or useable results for decision-making purposes. A manager who is responsible for justifying the allocation of limited funds will naturally be cautious about using models if he has the impression that they constitute a risky experiment.

Often a barrier to the more effective utilization of models is their output. Managers need to have model results presented in a way that is both meaningful and compatible with decisions that must be made. The uncertainties contained in various decision alternatives are especially important to assess. The form of the output is also important. Careful use of graphics and other displays may greatly enhance the utility of model results.

## Education of Managers

Technical experts often state that their problems in applying models would be greatly reduced if managers would learn more about modeling. While this is no doubt true, it may place unfair blame on managers. It is equally true that modelers and technical experts often fail to convey clearly to managers model results, the range of applicability, the limitations, and the degree of reliability of models. Unfortunately, the technical expert's abilities in inter-personal communication are often thwarted by his lack of attention to management needs and by the use of technical jargon. Terms such as "dispersion coefficients" and "piezometric heads" may be trade words of the modeler but are essentially meaningless to many managers.

While in general it is not reasonable to expect managers to enroll in courses in modeling, it is possible for managers to learn something about models through more active participation in the application of models to their problems. Involvement of managers in discussions of the relative importance of model inputs and of the necessity of defining constraints should lead to benefits of two sorts. First, the accuracy and value of the model output itself is likely to be improved, and second, the manager is more likely to make increased use of its output.

## Problem Definition

The concise statement of a problem is a prerequisite step in that problem's solution. However, the precise formulation of a management problem can be an extremely difficult task. Both managers and technical personnel often experience difficulty in isolating those factors which are critical for the application of a model to a problem and in formulating those factors in the precise terms required by models.

Nonetheless, the way in which a problem is defined affects how the professional expert approaches a solution. Thus, what general type of model is chosen -- provided, of course, that a model is deemed a proper analytical tool in the first place -- is determined by the problem definition. Improved problem definition is likely to result from more interactive participation of managers and technical personnel in model design and application.

## Acceptability of Management Models

Models for groundwater resource management ranked second in priority to prediction models among the needs expressed by the technical modeling experts surveyed by the project. Such models can be a productive method of gaining a better understanding of the system under study. Managers often find it difficult to state their objectives explicitly and quantitatively because of the multitude and noncommensurability of such objectives and because of political and institutional constraints. Similar difficulties preclude managers from utilizing the outputs of such models. Nonetheless, the potential utility of these models is great; the frequent requests for more management models indicate a growing interest in their application.

## Models in the Political and Legal Context

Models have become widely accepted and quite useful as tools for making engineering decisions. However, with the possible exception of Israel and France, models have not yet achieved great acceptance in the formulation of public policy in most countries. There are several reasons for the failure of policy-makers to utilize models. Individuals at higher levels of decision-making where policies are formulated often have less familiarity with models than the operations managers who use them for engineering decisions. There may also be institutional obstacles to the transfer of model-based decisions to policy decisions.

Model results may become embroiled in the inevitable conflicts that accompany matters of policy choice. In the United States many of these conflicts are resolved either politically or in the courts. The difficulties of using models as evidence in a court of law vary with the legal system; within the United States the legal system is not homogeneous. Much legislation regarding water is formulated at the state level; states differ on issues so apparently simple as the definition of groundwater. Furthermore, judges and lawyers alike are generally unfamiliar with the limits and capabilities of models, as well as with the technicalities of the problems which warrant model use. Resulting uncertainty makes the presentation of model results in court a generally risky and undependable undertaking.

Perhaps the most important factor inhibiting the effectiveness of models in the legal context is an apparently fundamental incompatibility between the models in their present state and the nature of the evidence required by a court of law. As mentioned earlier, models are built upon calculated assumptions and parameters at which a range of acceptable values may be given. In the courtroom, however, this lack of definitive output provides ample grounds for questioning the reliability of the model in use. An additional drawback is that technical witnesses are often unschooled in courtroom techniques or in the convincing rebuttal of objections to the models which are bound to be raised by skilled lawyers.

## DEFICIENCIES IN DATA

Inadequate or insufficient data were identified by many project respondents as being an important limiting factor in the use of models for groundwater resource management. While problems related to data are unquestionably of significance, it would also appear that data problems may obscure other difficulties in model use. A major reason for the emphasis on data among project respondents is the fact that data are frequently the largest single factor influencing the cost and benefits of using a model.

## Data Collection

Data receive a great deal of attention in part because they are recognized as the key factor limiting the kinds of models that can be applied to a problem and the degree of reliability of the model output, and because the acquisition of data on groundwater systems is a relatively expensive undertaking. In determining whether insufficient data are a real barrier to the successful application of a model to a problem, it is necessary first to determine the degree of accuracy that is required in the solution of the problem. In many cases it is not necessary to have highly accurate information to answer simple questions about a groundwater system. This is particularly true in regard to the initial development of an aquifer. As development proceeds, the degree of sophistication and accuracy of the model becomes more important. At the same time the amount of data available about the groundwater system will, or at least should increase.

In short, it is not fair to say that inadequate data preclude the use of a model. Nonetheless, these constraints may be serious. An important observation regarding data is that the progress in the use of computers to simulate groundwater systems has not been accompanied by parallel developments in data collection techniques. Data on groundwater systems are still collected largely by drilling wells -- a costly and time-consuming activity. Improved methods of data collection would unquestionably be of great value to the management of groundwater and would probably significantly reduce the costs of applying models.

An important process in data collection is the determination of which data are necessary to improve the reliability of model output. Thus, after a model has been run, it should be tested through sensitivity analysis in an effort to discover which are critical data to a particular application, that is, to discover what data most critically affect the model output. The results of this sensitivity analysis, coupled with the value of the expected improvements in model results, will determine what data are necessary to be collected for improving the model analysis.

## Parameter Identification Models

Closely related to collection of the input data is the determination of model parameters. These parameters are required for the calibration and validation of a model prior to its application to a particular field problem. A relatively new focal point of modeling research has been the development of models to deal specifically with parameter identification, or to solve what is technically known as the "inverse problem."

Considerable disagreement exists concerning both the reliability and utility of these models. On the one hand, some researchers maintain that expensive data collection efforts and time-consuming trial-and-error procedures could be circumvented by the development of reliable direct methods for parameter identification. Others feel that more effort should be directed toward the determination of parameters through field tests. In general, existing solutions to the inverse problem leave something to be desired -- and at present do not exist in a sufficiently sophisticated form to allow their widespread use.

## Data Manipulation

Another relatively new kind of model has been developed in an effort to design optimal data networks and data banks. Such models, as well as data manipulation codes, are particularly appropriate for situations in which long-term, comprehensive management of groundwater resources is envisioned. Data manipulation codes can also contribute to modeling efforts where large amounts of data already exist and require efficient organization and processing to prepare model inputs.

In spite of the frequently expressed needs concerning data, models for data manipulation were not often requested by technical experts in the project surveys. This may be due in part to an insufficient understanding of the models' potential utility, or to a lack of awareness of the models' existence. It is also possible that many professionals concerned with solving groundwater management problems, particularly those with consulting firms, must provide answers according to a demanding or short-term schedule. They thus have neither the time nor financial resources to be concerned with additional data collection which may be necessary for the long-term management of groundwater systems.

## Data Storage

As groundwater resources are increasingly developed, a considerable amount of data are amassed. These data are often collected by different agencies for a broad range of purposes, some of them totally unrelated to the management of the resource. Nevertheless, these data have great potential value for groundwater management both in terms of the description of the physical system and the history of its response to development. Thus, apart from programs for the design of data collection networks and the manipulation of data, there are also problems involved in the proper storage and retrieval of various kinds of information pertinent to groundwater management.

For this reason, it may be useful to have a centralized facility for the storage and retrieval of this information. Within the United States, the Water Resources Division of the U.S. Geological Survey has undertaken to develop such a central facility and to catalog the information for retrieval by interested agencies. Other countries may also find it useful to develop such facilities for the inventory of resources and the monitoring of their development.

A word of caution regarding data banks is in order. Experience has shown that some care must be taken that such facilities not become an expensive "dumping ground" for information. Some sort of screening of data must be undertaken to assure that they are both relevant and reliable. To this end, guidelines must exist on the kinds of data which should be stored and on standards for their validation.

## Simple versus Complex Models

Disputes over the relative merits of using simple or complex models to solve problems are not uncommon among those involved with groundwater management. It would appear that the level of sophistication of a model applied to a specific problem will be determined largely by the preexisting constraints upon that problem. As a rule the dominant constraint is data, or from another point of view, the costs of acquiring data.

There are of course other possible constraints, such as lack of credibility of models to managers or the time in which the problem must be solved.

In some cases simpler models may be justified. In others the technical expert may compromise by opting for simple models in the initial stages of analysis, and then progressively escalating to more complex models to reach more sophisticated levels of problem understanding, when economically justified. In any case situations should be avoided in which existing models preclude improved data collection or available data hamper the development of new models.

## DEFICIENCIES IN MODELING

A great deal of energy and resources have been directed in recent years to the field of groundwater modeling by government agenices, universities, and consulting firms. As a consequence, there are relatively few kinds of models that are both urgently needed and missing or seriously deficient. There are, nonetheless, areas where improvements in existing models are warranted, development of new models deserves further discussion and further basic research regarding models is desirable.

### Improvements in Existing Models

Respondents to the model surveys consistently identified several areas in which existing models could be improved for management applications. The transferability and flexibility of codes is often a barrier to utilization of models. A model, which is suitable by other criteria, may not be used because its code is not easily transferred from one computer to another or because its code is not easily integrated with other existing codes. Other barriers include computer storage and time requirements, and the instability, flexibility and utility of outputs. With proper effort, the codes of many existing models could be improved so as to overcome many of these problems.

### Prediction Models

Prediction models are well developed and considered to be reliable for most purposes, particularly the simulation of groundwater flow. During the course of the project, survey respondents frequently encourage the development of models that do in fact already exist. The fact that the existence of these models was not known to many technical experts highlights the problems discussed earlier in this chapter concerning the lack of accessibility of models to potential users.

Nevertheless, in spite of the relatively advanced level of development of prediction models, certain kinds of models are in fact missing or unsatisfactory. The use of the word "unsatisfactory" introduces a strong element of professional judgment into the identification of those model types which require further refinement. An attempt has been made here to find whatever consensus may be reached in such matters.

A great many project respondents expressed a desire to have models which fully integrate subsurface flow, and flow through the unsaturated zone. Such models do exist, but there is some dispute over their success in describing these phenomena and their ease of application. Models which describe flow and mass transport through media of secondary permeability, such as the fractured or karstic formations, were also identified as missing. Such models would be extremely useful in certain regions, and there is general agreement that existing solutions to the problems are inadequate.

In general, the unsaturated zone is a problem area. Models of unsaturated flow have been built, but they are not yet universally regarded as adequate. A complete understanding of the movement of pollutants in the unsaturated zone is lacking and of considerable importance. As previously noted, such models may have to await improved scientific understanding of the physical phenomena involved.

Contaminant transport models that include chemical and biological reactions are needed. Such non-conservative transport models are currently being developed, but they have not been adequately tested, at least in the opinion of some professionals.

Finally, models describing the flow of two immiscible fluids are felt to be missing for the groundwater profession. These models would be particularly useful for the analysis of the effects of waste disposal on the groundwater regime. The petroleum industry has conducted extensive research in this area, as well as developed sophisticated models of the process. These models may need to be adapted for groundwater problems.

## Stochastic versus Deterministic Models

An important issue in the current discussions of approaches to modeling is whether models of groundwater systems should contain randomly fluctuating variables known technically as stochastic inputs. While in recent years some models have been developed which contain stochastic inputs, particularly for variables such as recharge, model users disagree on the overall need for stochasticity in groundwater models.

Professionals arguing against the basic need for stochasticity maintain that the groundwater system acts to dampen these inputs to such an extent that their effects are negligible. They further maintain that the data available for many models is not sufficiently accurate or complete to justify a stochastic approach. Other model users, in contrast, point out that stochastic inputs may be extremely valuable in some situations, such as closely connected stream-aquifer systems and arid regions where a major portion of the 100-year recharge may come in a single season. Furthermore, stochasticity may be an important attribute of model parameters. Most experts, regardless of which side of the argument they support, agree that stochastic inputs are not adequately handled by existing models.

## General versus Specific Models

There appears to be little consensus among model users on the value of "generic models," or models which are intended for application to many different problems. While in theory such models are desirable, in practice they are difficult to develop and susceptible to misuse. To be utilized effectively, generic models ought to be relatively simple and well documented, since as the models become more complex, it becomes difficult for the uninitiated user to understand and use them properly. Generalized models may, however, be rather cumbersome and a model user may consequently prefer to modify a simpler model to a new problem. This can often be accomplished with relative ease, at low cost, and in a reasonable amount of time.

## The Role of Analog and Hybrid Models

The focus of this report is on numerical models which are now almost universally preferred for solutions to management problems demanding a more sophisticated approach than can be provided by simple analytical models. However, two other kinds of models are available: analog models and hybrid models.

Analog models were the first kinds of models of groundwater systems to be developed, and although they are no longer widely used for management, it appears that they still have a role to play in education. They are useful, not only for classroom purposes, but also for explaining groundwater phenomena to groups involved in or affected by water management decisions.

The coupling of an analog model, usually a resistance-capacitance network, with a digital computer to create a hybrid model can give excellent results. From the standpoint of performance, hybrid models may be preferable to purely numerical solutions for such problems as coupled surface/subsurface flow. The technological improvements in digital computers has outstripped the improvements in analog and other calculating techniques.

## Institutions for Model Development

Currently, models are being developed in several different institutional contexts including universities, consulting firms, and government agencies at a number of levels. Such dispersal of modeling activities inevitably leads to some duplication of effort. This duplication could be reduced, if not eliminated through better description of existing models and current modeling work in the literature. On the other hand, the diversity of types of organizations involved in modeling work is generally viewed as a strength in that the differing needs and approaches of various institutions probably encourage greatly the development of new methods and modeling techniques which in turn may lead to increased overall efficiency. Modeling involves the education of a group of technical experts. This widespread activity generally leads to better education of the modelers.

### Basic Research and Model Development

The fact that certain types of models have not been developed or are not considered reliable may be caused by factors not intrinsic to the models. Rather, the underlying theory concerning the systems to be modeled may not yet have been adequately described. In other words, there is a gap in our scientific understanding of certain physical and methodological phenomena. This gap will have to be filled through further observation of the phenomena in question and the development of adequate theories to describe them. Once these phenomena have been described, the incorporation of the necessary equations into models should provide to be a tractable problem.

There is not complete agreement about where these research gaps lie. However, four areas of particular concern did emerge during the course of the project: 1) an adequate description of the kinetics of chemical and biological processes; 2) the movement of pollutants through the unsaturated zone; 3) the quantification of management objectives; and 4) better parameter methodologies. Some of these gaps may be filled by a transfer of knowledge from other disciplines rather than by new research.

## ESTABLISHING PRIORITIES

The preceding sections of this chapter have presented in a discursive manner the findings of this project and have outlined some general conclusions concerning the difficulties and gaps in the use of models for groundwater management. Clearly, many of the problem areas that have been identified are interrelated; attempts to reach solutions should be pursued on a variety of fronts. On the other hand, it is not possible to move toward solutions on all fronts simultaneously. Some priorities must be established in order that the most serious problem areas may be addressed first. The recommendations of the project are presented in Chapter 2 of this report and reflect basic priorities as determined by the project steering committee and staff.

The intent of this report has not been to further scientific research or to improve upon existing technologies. Rather, the central focus of the project has been to increase the benefits to be derived from improved groundwater resource management. It is in this light of improved resource management that this state-of-the-art evaluation of groundwater models has been undertaken, and the project's recommendations are directed primarily toward this goal.

# APPENDIX A

## REVIEW OF SURVEYED NUMERICAL MODELS

### Introduction

The objective of this review is to familiarize the technical reader with the essential conceptual and mathematical details and the state of usability of each of the surveyed models. The information is discussed within the framework of the model taxonomy presented in Figure A-1 and is based on the following descriptors:

Systems
Processes
Purpose and/or Output
Geometry
Method
Special Features
Documentation
Availability
Past Applications

Most of the information is contained in a series of 26 tables which are summarized in Figure A-2. The order and form of presentation vary slightly from one model category to another. In general, the level of detail increases with the complexity of the models. A descriptive summary of each model category follows.

## PREDICTION MODELS

### Conceptual framework.

The surveyed prediction models serve the purpose of predicting the state of a single or multiphase hydrologic system, one phase of which is

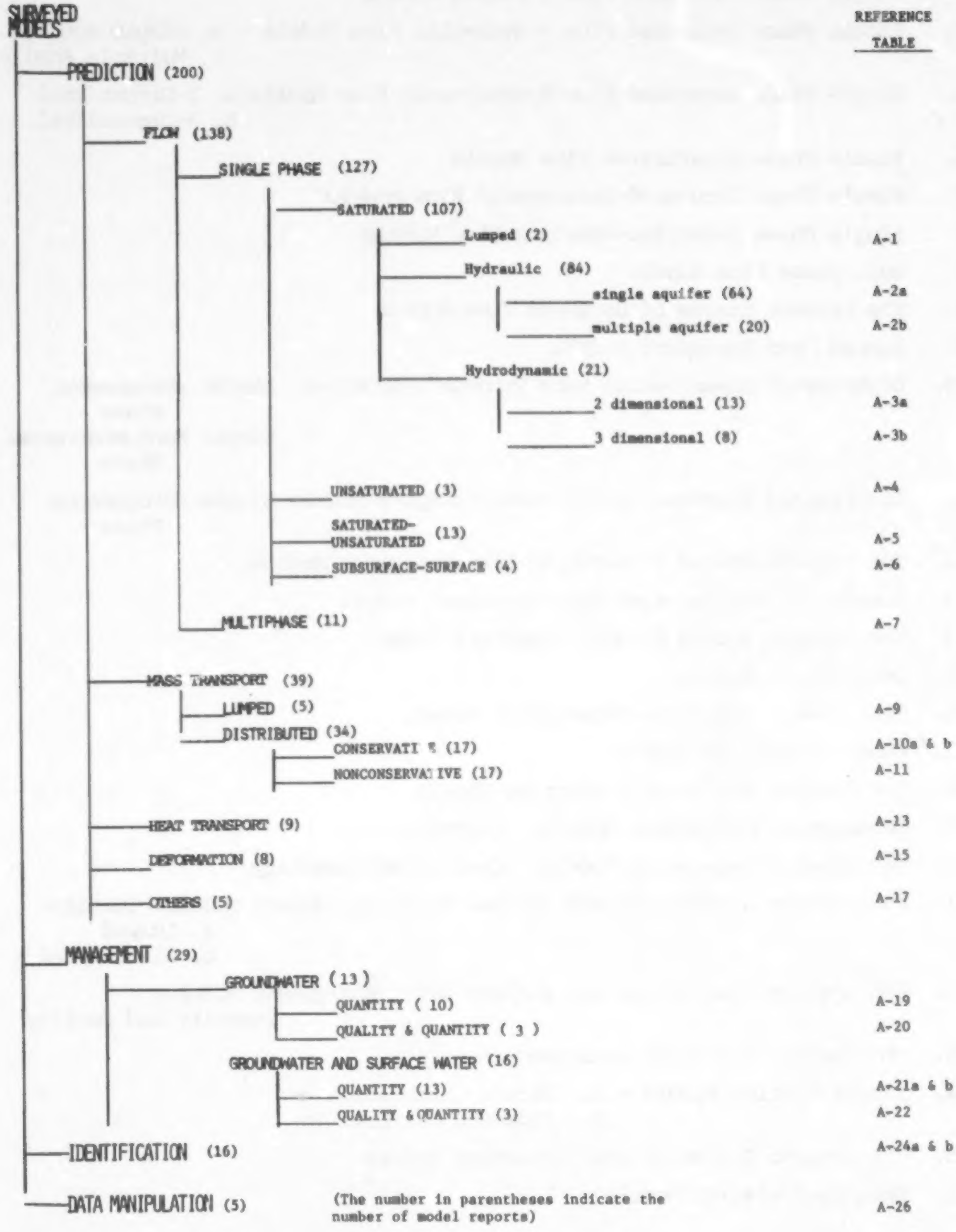

SURVEYED MODELS
REFERENCE TABLE
PREDICTION (200)
FLOW (138)
SINGLE PHASE (127)
SATURATED (107)
Lumped (2)
A-1
Hydraulic (84)
single aquifer (64)
A-2a
multiple aquifer (20)
A-2b
Hydrodynamic (21)
2 dimensional (13)
A-3a
3 dimensional (8)
A-3b
UNSATURATED (3)
A-4
SATURATED-UNSATURATED (13)
A-5
SUBSURFACE-SURFACE (4)
A-6
MULTIPHASE (11)
A-7
MASS TRANSPORT (39)
LUMPED (5)
A-9
DISTRIBUTED (34)
CONSERVATIVE (17)
A-10a & b
NONCONSERVATIVE (17)
A-11
HEAT TRANSPORT (9)
A-13
DEFORMATION (8)
A-15
OTHERS (5)
A-17
MANAGEMENT (29)
GROUNDWATER (13)
QUANTITY ( 10)
A-19
QUALITY & QUANTITY ( 3 )
A-20
GROUNDWATER AND SURFACE WATER (16)
QUANTITY (13)
A-21a & b
QUALITY & QUANTITY (3)
A-22
IDENTIFICATION (16)
A-24a & b
DATA MANIPULATION (5)
A-26
(The number in parentheses indicate the number of model reports)

Figure A-1. TAXONOMY OF SURVEYED MODELS

A-1. Single Phase Saturated Flow - Lumped Models
A-2. Single Phase Saturated Flow - Hydraulic Flow Models - a. Single Aquifer
  b. Multiple Aquifer
A-3. Single Phase Saturated Flow-Hydrodynamic Flow Models-a. 2-Dimensional
  b. 3-Dimensional
A-4. Single Phase Unsaturated Flow Models
A-5. Single Phase Saturated-Unsaturated Flow Models
A-6. Single Phase Subsurface-Surface Flow Models
A-7. Multiphase Flow Models
A-8. The Present Status of Surveyed Flow Models
A-9. Lumped Mass Transport Models
A-10. Distributed Conservation Mass Transport Models-a. Single Homogeneous Phase
  b. Single Nonhomogeneous Phase
A-11. Distributed Nonconservative Mass Transport Models-Single Homogeneous Phase
A-12. The Present Status of Surveyed Heat Transport Models
A-13. Summary of the Surveyed Heat Transport Models
A-14. The Present Status of Heat Transport Models
A-15. Deformation Models
A-16. The Present Status of Deformation Models
A-17. Other Prediction Models
A-18. The Present Status of Prediction Models
A-19. Groundwater Management Models: Quantity
A-20. Groundwater Management Models: Quality and Quantity
A-21. Conjunctive Groundwater and Surface Water Management Models: Quatity-
  a. Lumped
  b. Distributed
A-22. Conjunctive Groundwater and Surface Water Management Models: Quantity and Quality
A-23. The Present Status of Management Models
A-24. Identification Models - a. Direct Calibration
  b. Indirect Calibration
A-25. The Present Status of Identification Models
A-26. Data Manipulation Models

Figure A-2. LIST OF TABLES

usually moving groundwater. Other fluid phases comprising the system may be either mobile or immobile, yet the terms single or multiphase pertain to the mobile phases only. A fluid phase is referred to as homogeneous if its density and viscosity are uniform in space. Otherwise it is nonhomogeneous.

The processes described by the prediction models include flow of fluid, transport of mass and/or heat, and deformation. Transport processes are nonconservative if transformations by reactions and phase change are involved; otherwise the processes are conservative. Immiscible transport occurs by convection alone, miscible transport occurs by convection with dispersion and/or conduction, as well. Processes may be defined as either steady or nonsteady. Mass, heat transport, and deformation are usually considered as nonsteady.

The spatial domain in which the processes occur may include the saturated zone, the unsaturated zone and/or the zone of surface water. The subsurface part of the domain is heterogeneous with regard to the hydrologic parameters, unless otherwise stated. It may also be anisotropic. The external boundaries of the domain are considered to be immobile unless otherwise specified. The representation of the spatial domain may be lumped or distributed. In the later case the domain is considered as an assembly of discrete interconnected cells or blocks. Sources and sinks of fluid volume, mass or heat, if present, are aggregated over a cell and/or over a time step if the process is nonsteady.

The common output of a prediction model includes values of state variables, such as head for flow models, head and concentration of constituents for mass transport models, head and temperature for heat transport, and displacement of the ground surface for deformation models. Additional output variables for special purpose models are noted in the tables. The input and output of all prediction models are deterministic. The majority of the models pertain to nonsteady processes. Each transport model includes a flow submodel. Figure A-3 summarizes the tasks which the surveyed distributed prediction models can address and relevant typical outputs.

### Mathematical framework.

The output of a prediction model usually results from solving field equations under given boundary and initial conditions. The field equations

| Area | Typical Output | Number of Models | Distribution by Model Categories | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Flow | | | | | Mass Transport | | | | | | | Heat Transport | | | Deformation | Others |
| | | | Single Phase | | | | Multi-Phase | Conservative | | | | Nonconservative Homogeneous | | | Conservative | | Nonconservative | | |
| | | | | | | | | Homogeneous | | | Non-Homogeneous | | | | | | | | |
| | | | Unsat. | Sat. | Sat. Unsat. | Subsurface & surface | | Unsat. | Sat. | Sat. Unsat. | | Unsat. | Sat. | Sat. Unsat. | Unsat. | Sat. | | | |
| General | Head | 7 | 2 | 57 | 9 | 1 | 1 | | | | | | | | | | | | |
| | concentr. | 31 | | | | | | 3 | 9 | 2 | | 4 | 10 | 3 | | | | | |
| | Temperature | 4 | | | | | | | | | | | | | 1 | 3 | | | |
| | combinations of the above | 3 | | | | | | | | | | | | | | | | | 3 |
| Stream-aquifer relation | Head & flow | 19 | | 16 | | 3 | | | | | | | | | | | | | |
| Flow Pattern | Streamlines, fronts, travel times | 9 | | 7 | | | 2 | | | | | | | | | | | | |
| Interface (fresh-salt water) | Position | 8 | | 2 | | | 6 | | | | | | | | | | | | |
| | Dispersion zone | 2 | | | | | | | | | 2 | | | | | | | | |
| Free surface | Position | 8 | | 8 | | | | | | | | | | | | | | | |
| Well performance | Drawdown | 6 | | 5 | | | 1 | | | | | | | | | | | | |
| | concentr. | 1 | | | | | | | | | 1 | | | | | | | | |
| | Temperature | 3 | | | | | | | | | | | | | | 3 | | | |
| Geothermal reservoirs | Pressure, saturation temperature | 4 | | | | | 1 | | | | | | | | | 1 | 1 | | 1 |
| Deformation of land surface | Subsidence | 6 | | | | | | | | | | | | | | | | 6 | |
| | Subsidence & lateral displacement | 2 | | | | | | | | | | | | | | | | 2 | |
| Aid in management | Response coeffic. Head & flow | 5 | | 4 | 1 | | | | | | | | | | | | | | |
| Water & crop relationship | Evapotranspiration | 4 | 1 | | 3 | | | | | | | | | | | | | | |
| Accumulation of sediments | Pressure temperature | 1 | | | | | | | | | | | | | | | | | 1 |
| Flow in Karst | Discharge | 1 | | 1 | | | | | | | | | | | | | | | |
| Frost propagation | Frost line | 1 | | | | | | | | | | | | | | | | | 1 |
| Prediction & calibration | Error | 5 | | 5 | | | | | | | | | | | | | | | |
| Total | | 193 | 3 | 105 | 13 | 4 | 11 | 3 | 9 | 2 | 3 | 4 | 10 | 3 | 1 | 7 | 1 | 8 | 6 |

Figure A-3. PURPOSE AND OUTPUT OF SURVEYED DISTRIBUTED PREDICTION MODELS are termed transport equations for mass and heat transport and flow equations for fluid volume transport. Any field equation is a combination of a balance equation of the transported or transformed entity (fluid volume, mass, heat) and phenomenological equations which relate the process undergone by the entity to the properties of the material in which it occurs. The equations and conditions are usually based on a conceptual model of a physical system. However, a few of the codes contain transformation functions of a parametric nature (e.g. lumped input-output functions).

Models are classified as linear or nonlinear according to the mathematical relationship between the field equation and the relevant output variable. Thus, a linear flow model implies that the flow equation is linear with respect to the head. Usually, the equations and the conditions contained in a model are given in a differential form. Various numerical methods can then be used to transform the field equations into a set of algebraic equations with one equation required for each node or cell and/or time step. The most common numerical methods employed are finite differences (F.D.) and finite elements (F.E.). Other less common numerical methods include characteristics and random walk, which are used for mass transport models.

Once the set of algebraic equations is established it is then solved for the output variable. Various techniques are used for solving the large sets of simultaneous equations generated by either one of the above methods. Iterative techniques such as successive overrelaxation, Gauss-Siedel and iterative ADI are the most common. Direct matrix inversion techniques such as tridiagonal algorithms and Gauss elimination are also used. In some cases special equation-solving algorithsm have been designed. They are indicated in the review tables under "special features."

Most of the numerical solutions become unstable under extreme conditions and convergence of the numerical solution to an exact solution cannot in general be assured. For some iterative methods the change in the output between consecutive iterations is used as a criterion for the convergence of the computational scheme.

Some of the surveyed codes bypass the need to form and solve equations by adopting existing analytic solutions and performing only a numerical approximation of such solutions. This method is usually applied to models which assume an ideal homogeneous and istropic medium and linear processes. Extensive use of the principles of superposition and images is common in this group of codes.

Figure A-4 summarizes the mathematical methods used in the various categories of prediction models surveyed.

Specific Model Characteristics.

Flow. Only the flow of homogeneous fluids has been considered. The flow of nonhomogeneous fluids is treated with the mass and/or heat transport models. The terms single phase, multiphase, saturated, unsaturated, saturated-unsaturated, subsurface and surface flow refer to the type of phases or hydrologic domains for which flow equations are present in the model.

All flow models, but one, are based on the Darcy law. Those distributed flow models which are also based on the Dupuit approximation are termed hydraulic flow models. To this group belong one-dimensional and two-dimensional models of horizontal flow in a single or multiple leaky or non-leaky aquifer system, with a vertical leakage component. Saturated-unsaturated flow models with horizontal flow in the saturated zone and vertical flow in the unsaturated zone are also considered hydraulic flow models.

The hydraulic flow equations are linear with respect to head and have constant transmissivity for confined or semiconfined flow conditions. Under phreatic flow conditions the hydraulic conductivity is assumed constant whereas the transmissivity is head dependent and adjustable at each time step. For both conditions the storativity is assumed constant in time. Some codes automatically change the value of storativity on passing from confined to phreatic conditions and vice versa.

Distributed flow models which do not use the Dupuit approximation are termed hydrodynamic. Models with two-dimensional flow in the vertical plane or three-dimensional flow belong to this group.

For single phase models covering the unsaturated zone it is assumed that the air phase in that zone is immobile and under atmospheric pressure and that the hydraulic conductivity and the capillary pressure are functions of the water content. For joint multiphase flow models, both the water and the air phases are assumed to be mobile and to occupy the same

| Purpose and Output | | Total Number or Reports | Methods of distributed prediction models | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Analytic Approximation | F.D. | F.E. | F.D. or F.E. | Characteristics | F.D. or Char. | Hybrid | Random Walk | Others |
| General: | Head | 70 | 4 | 47 | 17 | | | | | | 2 |
| | Concentration | 31 | 1 | 13 | 8 | 1 | 5 | 1 | 1 | 1 | |
| | Temperature | 4 | | 3 | 1 | | | | | | |
| | Combinations of the above | 3 | | 1 | 2 | | | | | | |
| Stream-aquifer relation | | 19 | 1 | 15 | 3 | | | | | | |
| Flow Pattern | | 9 | 4 | 2 | 1 | | | | | | 2 |
| Interface | Position | 8 | | 5 | 2 | | | | | | 1 |
| | Dispersion Zone | 2 | | | 2 | | | | | | |
| Free Surface | | 8 | | 2 | 3 | 3 | | | | | |
| Wells | Drawdown | 6 | | 6 | | | | | | | |
| | Concentration | 1 | | 1 | | | | | | | |
| | Temperature | 3 | 2 | 1 | | | | | | | |
| Geothermal reservoirs | | 4 | | 3 | | 1 | | | | | |
| Subsidence | | 8 | | 5 | 3 | | | | | | |
| Aid in management | | 5 | | 5 | | | | | | | 1 |
| Water and Crop | | 4 | | 3 | | | | | | | |
| Sediment Accumulation | | 1 | | 1 | | | | | | | |
| Flow in Karst | | 1 | | 1? | | | | | | | |
| Frost Propagation | | 1 | | 1 | | | | | | | |
| Prediction & Calibration | | 5 | | 5 | | | | | | | |
| TOTAL | | 193 | 12 | 117 | 45 | 5 | 5 | 1 | 1 | 1 | 6 |

Figure A-4. MATHEMATICAL METHODS USED IN SURVEYED DISTRIBUTED PREDICTION MODELS domain. For disjoint multiphase flow models such as those which handle the movement of the interface between moving fresh and salt water in a coastal aquifer, the phases are assumed to occupy separate domains with distinct macroscopic boundaries between them. A detailed summary of the flow models is given in Tables A-1 - A-7. Information on additional lumped flow submodels can be found in Table A-9 (lumped mass transport models) and in Tables A-21 and A-22 (conjunctive management of groundwater and surface water). Additional distributed flow submodels can be found in Tables A-10 and A-11 (mass transport models), in Table A-13 (heat transport models), in Table A-17 (other prediction models) and in Tables A-19 through A-22 (management models).

Mass Transport. Mass transport models solve the mass transport equation for each constituent in each phase with a velocity input from a flow model. If the phase is nonhomogeneous the velocity is concentration dependent and hence flow and mass transport have to be coupled at each time step. If the phase is homogeneous the two are independent and if flow conditions are steady the velocity field can then be derived in one step. Nonisothermal mass transport is considered in the context of a mass and heat transport model under the category of "other prediction models."

A weakness of the numerical mass transport models, especially of those employing finite differences, is the phenomenon of numerical dispersion which results from the spread of a constituent entering a cell instantaneously over the entire cell. The numerical dispersion of immiscible transport models overshadows the physical dispersion of miscible transport models while analytical solutions are free of this problem. Some lumped models attempt to reduce the effect of numerical dispersion by introducing an effective mixing depth. Some distributed models use the method of characteristics whereby individual particles rather than the total mass are moved between cells in order to reduce the effect of numerical dispersion.

A detailed summary of the surveyed mass transport models is given in Tables A-9 - A-11. Other models which include a mass transport component can be found in Table A-17 (Other prediction models) and in Tables A-20 and A-22 (Quality management models).

Heat transport. Unlike mass, heat can also be transmitted through the solid phase and/or stored in it. Also, in addition to the mass transport mechanisms, heat can be transferred by conduction and radiation. However, the surveyed heat transport models consider convection and conduction only. Flow and heat transport are coupled whenever the density and/or viscosity of the fluid phase is temperature dependent.

A detailed summary of the surveyed heat transport models is given in Table A-13. Additional models containing a heat transport submodel are listed in Table A-17 (Other prediction models).

Deformation. A deformation model computes the deformation of the solid Matrix of a porous medium by using the change in stress or head in that medium obtained from a flow model. The deformation may be either elastic or nonelastic and accordingly the mathematics required will vary from relatively simple to complex.

In the simplest version of a deformation model the flow parameters are considered constant. In this case, the flow and deformation submodels can be uncoupled. A more realistic version assumes that the flow parameters are stress-dependent through changes in porosity. In this case the two submodels have to be coupled for each time step.

A detailed summary of the surveyed deformation models is given in Table A-15. Additional deformation submodels can be found in Table A-17 (Other prediction models).

Coupled and other processes. Codes have recently been developed which deal with coupled mass and heat transport, transport in a deformable medium, and for solving multipurpose flow or transport problems. These codes, together with others which do not belong to any of the categories listed above, are classified as "other prediction models" and are summarized in Table A-17.

### Evaluation

A matrix of model space was prepared for each subcategory of prediction models and models surveyed were superimposed on that matrix. The results are presented in Tables A-8, A-12, A-14 and A-16.

Models surveyed in a given area are identified by their respective numbers or by an X in the case of the flow models. Circles indicate usable models, namely models which are fully documented, available and have been applied to a field problem once or more. Blank spaces in each table indicate areas for which models do not exist. It must be emphasized that the existence of a blank space does not necessarily indicate that models of that type are needed to improve groundwater-related water resource management. A summary of the present status of prediction models follows.

Flow models (Table A-8): Missing completely are stochastic flow, deterministic non-Darcian flow, and multipurpose conjunctive subsurface and surface flow. Within the area covered by existing models, some models are missing for special tasks such as well hydraulics in single and multiple aquifers as well as flow patterns and interfaces in multiple aquifers.

Mass transport (Table A-12): Adequately treated are conservated and nonconservative miscible transport processes in a single homogeneous phase containing one or more constituents undergoing first order reactions under equilibrium conditions. Nonhomogeneous phases, nonlinear reactions and biochemical reactions in particular are just beginning to be considered. Nonequilibrium conditions, multiphase transport phenomena and stochasticity of transport processes have not as yet been considered.

Heat transport (Table A-14): The major area of development is that of conservative linear heat transport in a single homogeneous or nonhomogeneous fluid phase. Nonconservative and nonlinear heat transport as well as transport of heat in a multiphase fluid system have just begun. Heat transport in a disjoint multiphase system and stochasticity have not been considered as yet.

It is worthwhile noting that while mass transport covers both the saturated and saturated-unsaturated zones, all but one of the heat transport models are confined to the saturated zone and to a nonconducting solid phase.

Deformation (Table A-16): Most of the deformation models have been developed and applied to elastic subsidence in conjunction with a hydraulic flow model. In addition, one deformation model treats elastic and nonelastic subsidence which is coupled with flow. Another model treats subsidence with lateral displacement in a vertical plane which is uncoupled with flow. The next steps would be to consider coupling for the later and three-dimensional deformation.

Concluding remarks. Table A-18 summarizes the present status of the prediction models. It shows that flow and mass transport phenomena are relatively well covered, but only at the distributed level and for a homogeneous single phase. Both the saturated and saturated-unsaturated zones, have been treated whereas few examples of conjunctive surface-subsurface transport models exist.

Some beginnings have been made in treating nonhomogeneous as well as multiphase and multicomponent transport phenomena, both linear and nonlinear. However, these areas call for further and more active development.

## MANAGEMENT MODELS

Conceptual framework:

Management models are a category of numerical models which serve the purpose of selecting decisions pertinent to the management of water resources containing groundwater. The relevant management tasks may include supply, water quality control, wastewater disposal and reuse, and protection of the environment. The decisions addressing these tasks include engineering (development, operation) and economics (resource allocation, prices, taxes and rebates).

Dynamic decisions are made for each time step within a given planning horizon. They are given either as sets of values of decision variables or as a policy (operating rules) whereby a decision is a function of the state of the systems concerned (e.g. water levels, level of development of the water supply system). The latter usually apply to cases where the input to the system is stochastic.

The hydrologic system (groundwater or groundwater and surface water) is a component of the surveyed management models. A technologic system is also present, ranging from water supply to water use and production of goods. The common state variables of the hydrologic system are storage, head, salinity and surface water flow rates. Examples of decision variables are location and capacity of wells (development), pumping and recharge rates (operations), and acreage of crops (production). Economic decision variables include investment, prices and taxes.

Constraints on admissible decisions and/or outcomes include levels of water supply or disposal, sources of supply, water rights, capacities of facilities, water levels and salinity and acreage of crops. While objective functions are usually economic, some models address physical or technical objectives such as maximum yield, maximum water levels, and satisfaction of water quality standards or demand.

## Mathematical framework.

The majority of the management models employ optimization techniques. Policy decisions with stochastic inputs are usually handled by stochastic-dynamic programming. Operational decision models which are usually deterministic employ other programming techniques, both linear and nonlinear. Some of them combine an optimization submodel which produces a decision at any time step, with a simulation submodel which predicts the resulting state as an input to the next decision. Others incorporate a simulation submodel in the formulation of the constraints, thus ensuring an overall optimum. The utilization of the so-called algebraic technological functions (ATF) makes these computations simpler.

Recently techniques of decomposition have been introduced for treating large scale systems. Multilevel optimization with an iterative coordinating algorithm has also been introduced as a methodology to ensure the compatibility of decisions made at different management levels. Another development is the use of decision theory to rank data by importance to management.

Further details of the surveyed management models are given in Tables A-19 - A-22.

## Evaluation

An evaluation of the surveyed management models is presented in

Table A-23. Most of the models address water supply problems from an engineering perspective. The majority of the models consider a distributed hydraulic system under deterministic conditions. Although some lumped models do exist for managing groundwater and surface water under stochastic conditions, they are dimensionally restricted.

Table A-23 indicates that water quality management models are in their infancy as are multilevel management decision models. Both lumped and hydrodynamic groundwater management models are lacking. The former are important for evaluating regional planning and the latter are important for evaluating water quality projects. Finally, models for addressing multiple objectives are lacking and would be useful for a variety of planning situations.

## IDENTIFICATION MODELS

### Conceptual framework.

Identification models attempt to find optimal estimates of unknown parameters and/or terms in a field equation of a prediction model. Such estimates are obtained by finding the extreme value of a norm of optimality often referred to as an objective function. "Best" estimates of parameters imply that the error of prediction resulting from these estimates can be assumed to fall within a prescribed interval at a given confidence level. The difficulties involved in obtaining them are both conceptual and technical. Among these are the inadequacy of available data, the lack of knowledge on the probability distribution and dynamic character of the estimated parameters, the application of constraints to parameter values, error criteria to be employed in determining the "best" values and the methods of optimization.

### Mathematical framework.

Two approaches to calibrating a prediction model are commonly utilized. In the direct method the input and output data are taken as given and the field equation is solved for the unknown parameters. In the indirect method the input data and the parameters are taken as known and the field equation is solved for the output in a succession of steps while correcting the parameters after each step. The indirect approach is by definition iterative and uses gradient search techniques. The direct approach may use either noniterative or iterative algorithms, the parameter values may be constrained or unconstrained and the optimization methods employed usually include least squares and mathematical programming.

The surveyed direct identification codes are usually calibrated using a volume balance equation, whereas the indirect codes are calibrated using a head prediction equation. An exception of this regard are three direct identification codes which calibrate equations with lumped response coefficients or functions. Further details of the surveyed identification codes are presented in Table A-24.

## Evaluation

Table A-25 presents an evaluation of the surveyed identification models. The models address parameter calibration for flow models only. Moreover, only one model (70-13) is able to provide statistical error information regarding parameter estimates. Another model (70-6) seems to have overcome by decomposition and iteration the difficulty of directly calibrating a multicell aquifer model. Three models (70-7, 70-8, 70-9) employ response functions which are important because of their potential for management and reduced computational requirements. Further progress depends on resolving the conceptual and computational difficulties discussed above.

## DATA MANIPULATION MODELS

The details of the surveyed data manipulation models are presented in Table A-26. The small sample indicates that this area is still in its initial stage of development.

TABLE A-1. SINGLE PHASE SATURATED FLOW: LUMPED MODELS

| Purpose or Output | System | Processes | Methods | Documentation | Availability | Past Applications | Identification | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Model No. | Country | Institution | Reporter (Year)* |
| Calculation of water balance and prediction of piezometric head | Unit basin | Pumpage and recharge | F.D. | Complete (Japanese) | Yes | Field (subsidence, irrigation, sea water intrusion) | 11-1 | Japan | Private | Shibasaki (67) |
| Prediction of head, flow, and components of water balance | One replenishable free surface reservoir drained through three parallel confined and linear reservoirs | Infiltration, evaporation and discharge | Numerical approximation of an analytical solution with an exponential decay function | Complete (French) | Yes | Field, karstic aquifer | 11-2 | France | Government | Bezes (76) |

*The number in the parentheses indicates the year of development of the model.

TABLE A-2a. SINGLE PHASE SATURATED FLOW: HYDRAULIC FLOW MODELS - SINGLE AQUIFER (continued)

| Purpose | Dynamics | Flow (Hydraulics) | Con- straints | Method | Documen- tation | Avail- ability | Past Appli- cations | Identification | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Model No. | Country | Institution | Reporter |
| Prediction of Head | | | | | 1 Dimensional | | | | | | |
| | 2 | 2 | 0 | 6 | 3 | 0 | 2 | 12-1 | U. K. | Geo. Sci. | Kitching |
| | | | | | 2 Dimensional | | | | | | |
| | 2 | 3 | 0 | 6 | 3 | 0 | 2 | 12-2 | France | SCET-International | Bonnier |
| | 2 | 4 | 1 | 6 | 5 | 2 | 2 | 12-3 | U. S. | Govt. | Prickett |
| | 2 | 4 | 0 | 6 | 3 | 3 | 2 | 12-4 | Japan | Govt. | Shibasaki |
| | 2 | 4 | 0 | 6 | 4 | 2 | 1 | 12-5 | Canada | Govt. | Vandenberg |
| | 2 | 5 | 0 | 7 | 2 | 1 | 2 | 12-6 | U. S. | Princeton U. | Pinder |
| | 3 | 5 | 0 | 6 | 2 | 0 | 2 | 12-7 | France | SGAL | Vancon |
| | 2 | 5 | 1 | 6 | 4 | 0 | 2 | 12-8 | U. K. | Govt. | Bibby |
| | 2 | 5 | 1 | 6 | 4 | 0 | 2 | 12-9 | U. K. | Private | Ashley |
| | 2 | 5 | 0 | Hybrid | 3 | 2 | 2 | 12-10 | U. K. | Univ. | Rushton |
| | 1 | 6 | 0 | 7 | 1 | 2 | 1 | 12-11 | Netherlands | Delft Univ. | Verruijt |
| | 2 | 6 | 0 | 6 | 3 | 2 | 2 | 12-12 | U. S. | Govt. | Prickett |
| | 2 | 6 | 0 | 6 | 1 | 2 | 2 | 12-13 | India | Govt. | Shah |
| | 2 | 2 | 0 | 6 | 3 | 2 | 2 | 12-14 | Israel | Private | Shamir |
| | 2 | 2 | 0 | 6 | 4 | 0 | 2 | 12-15 | U. K. | Govt. | Davis |
| | 2 | 2 | 0 | 6 | 3 | 0 | 2 | 12-16 | France | Govt. | Wolsack |
| | 2 | 2 | 1 | 6 | 4 | 2 | 2 | 12-17 | U. S. | Govt. | Knowles |
| | 2 | 2 | 1 | 6 | 3 | 2 | 2 | 12-18 | U. K. | Univ. | Rushton |

TABLE A-2a. SINGLE PHASE SATURATED FLOW: HYDRAULIC FLOW MODELS - SINGLE AQUIFER (continued)

| Purpose | Dynamics | Flow (Hydraulics) | Con-straints | Method | Documen-tation | Avail-ability | Past Appli-cations | Identification | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Model No. | Country | Institution | Reporter |
| | 2 | 2 | 0 | 6 | 7 | 0 | 2 | 12-19 | France | ARLAB | Blanc |
| | 2 | 2 | 0 | 6 | 3 | 0 | 2 | 12-20 | U. K. | Geo. Sci. | Adams |
| | 2 | 2 | 0 | 7 | 3 | 0 | 2 | 12-21 | Germany | Univ. | Klenke |
| | 2 | 2 | 0 | 1 | 7 | 0 | 2 | 12-22 | France | ARLAB | Baradat |
| | 3 | 2 | 0 | 6 | 1 | 0 | 2 | 12-23 | France | Univ. | Cazal |
| | 3 | 2 | 0 | 6 | 3 | 2 | 0 | 12-24 | N. Z. | Univ. | Hunt |
| | 3 | 2 | 0 | 7 | 7 | 0 | 9 | 12-25 | France | ARLAB | Blanc |
| | 3 | 2 | 0 | 7 | 3 | 0 | 2 | 12-26 | Germany | Govt. | Briechle |
| | 2 | 2 | 0 | 6 | 4 | 2 | 2 | 12-27 | U. K. | Univ. | Chidley |
| | 1 | 2 | 0 | 7 | 1 | 2 | 3 | 12-28 | Netherlands | Private | Olsthoorn |
| | 2 | 1 | 0 | 6 | 3 | 9 | 2 | 12-29 | U. S. | Univ. | Sunada |
| | 2 | 1 | 1 | 6 | 4 | 2 | 2 | 12-30u | U. K. | Battelle | Kipp |
| | 2 | 1 | 0 | 6 | 1 | 0 | 2 | 12-31 | U. K. | Govt. | Aldrick |
| | 2 | 1 | 0 | 6 | 9 | 3 | 2 | 12-32 | Belgium | Univ. | Bastin |
| | 2 | 1 | 0 | 6 | 3 | 9 | 0 | 12-33 | U. K. | Govt. | Keating |
| | 2 | 1 | 0 | 6 | 3 | 9 | 2 | 12-34 | U. S. | Univ. | Claborn |
| | 2 | 1 | 0 | 1 | 3 | 2 | 2 | 12-35 | Australia | Govt. | Colville |
| | 2 | 1 | 0 | 1 | 3 | 2 | 2 | 12-36 | Australia | Govt. | Colville |

TABLE A-2a. SINGLE PHASE SATURATED FLOW: HYDRAULIC FLOW MODELS - SINGLE AQUIFER (continued)

| Purpose | Dynamics | Flow (Hydraulics) | Con-straints | Method | Documen-tation | Avail-ability | Past Appli-cations | Identification | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Model No. | Country | Institution | Reporter |
| Stream Aquifer Relation | 2 | 1 | 0 | 6 | 3 | 2 | 1 | 12-37 | Canada | Govt. | Lin Chang, L. |
| | 2 | 1 | 0 | 6 | 3 | 2 | 2 | 12-38 | U. S. | Univ. | Brutsaert |
| | 2 | 2 | 0 | 6 | 3 | 2 | 0 | 12-39 | Canada | Govt. | Lin Chang, L. |
| | 2 | 2 | 0 | 6 | 3 | 9 | 2 | 12-40 | U. S. | Univ. | Grannemann |
| | 2 | 2 | 0 | 6 | 9 | 9 | 2 | 12-41 | U. K. | Govt. | Morel |
| | 2 | 2 | 0 | 7 | 3 | 2 | 2 | 12-42 | U. S. | U.S.G.S. | Hurr |
| | 2 | 3 | 0 | 6 | 3 | 2 | 2 | 12-43 | Australia | Univ. | Volker |
| | 2 | 4 | 0 | 6 | 4 | 2 | 2 | 12-44U | U. S. | U.S.G.S. | Reed |
| | 2 | 5 | 0 | 6 | 3 | 9 | 2 | 12-45 | Germany | Univ. | Mehlhorn |
| | 2 | 5 | 0 | 6 | 3 | 9 | 2 | 12-46 | U. S. | Univ. | Sunada |
| | 2 | 6 | 0 | 1 | 3 | 9 | 2 | 12-47 | U. S. | Univ. | Sunada |
| Prediction and Calibration | 2 | 2 | 0 | 6 | 2 | 2 | 2 | 12-48 | Israel | TAHAL | Blank |
| | 2 | 2 | 1 | 6 | 2 | 2 | 2 | 12-49 | U. K. | Univ. | Goodwill |
| | 2 | 2 | 1 | 6 | 3 | 0 | 2 | 12-50 | U. K. | Geo. Sci. | Kitching |
| | 2 | 5 | 1 | 6 | 5 | 0 | 2 | 12-51 | Argentina (U. N.) | Govt. | Navarro |
| | 2 | 9 | 0 | 6 | 2 | 2 | 1 | 12-52 | U. S. | Univ. | Simpson |

TABLE A-2a. SINGLE PHASE SATURATED FLOW: HYDRAULIC FLOW MODELS - SINGLE AQUIFER

| Purpose | Dynamics | Flow (Hydraulics) | Con-straints | Method | Documen-tation | Avail-ability | Past Appli-cations | Identification | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Model No. | Country | Institution | Reporter |
| Response Coefficients | 2 | 2 | 0 | 6 | 3 | 2 | 9 | 12-53 | U. S. | U.S.G.S. | Maddock |
| | 2 | 2 | 0 | 6 | 4 | 2 | 0 | 12-54 | U. S. | Univ. | Morel-Seytoux |
| | 3 | 2 | 1 | 6 | 3 | 9 | 2 | 12-55 | Israel | TAHAL | Schwarz |
| Stream-lines Fronts | 1 | 4 | 0 | 1 | 4 | 2 | 2 | 12-56 | Netherlands | Govt. | Van Den Akker |
| | 1 | 6 | 1 | 1 | 2 | 2 | 2 | 12-57 | Netherlands | Govt. | Van Den Akker |
| | 2 | 6 | 0 | 1 | 2 | 2 | 3 | 12-58 | Netherlands | Govt. | Van Den Akker |
| | 3 | 1 | 0 | 6 | 5 | 0 | 2 | 12-59 | U. S. | Battelle | Friedrichs |
| | | | 0 | 1 | 4 | 2 | 2 | 12-60 | U. S. | Boeing | Nelson |
| | | | 0 | 6 | 5 | 2 | 1 | 12-61 | Canada | Govt. | Vandenberg |
| | | | 0 | 1 | 7 | 0 | 2 | 12-62 | France | ARLAB | Baradat |
| Karst | 1 | Pipe flow | 0 | 6 | 4 | 9 | 2 | 12-63 | U. S. | Univ. | Thrailkill |
| Interface | 2 | 1 | 0 | 6 | 4 | 9 | 2 | 12-64 | Argentina | Govt. | Navarro |

TABLE A-2b. SINGLE PHASE SATURATED FLOW: HYDRAULIC FLOW MODELS - MULTIPLE AQUIFER (continued)

| Purpose | Dynamics | Flow (Hydraulics) | Con-straints | Method | Documen-tation | Avail-ability | Past Appli-cations | Identification |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  |  |  | Model No. | Country | Institution | Reporter |
| Prediction of Head |  |  |  |  |  |  |  |  |  |  |  |
|  | 2 | 2 | 1 | 6 | 1 | 0 | 2 | 13-1 | U.S. | Private | Kleinecke |
|  | 3 | 2 | 0 | 6 | 7 | 9 | 2 | 13-2 | Germany | Govt. | Giesel |
|  | 3 | 2 | 0 | 6 | 7 | 0 | 2 | 13-3 | France | Private | Clouet D'Orval |
|  | 2 | 2 | 1 | 6 | 4 | 0 | 2 | 13-4 | U.K. | Govt. | Liddament |
|  | 1 | 5 | 0 | 7 | 7 | 0 | 2 | 13-5 | Netherlands | Govt. | Fillekes |
|  | 2 | 5 | 0 | 6 | 2 | 0 | 2 | 13-6 | France | Private | Carriere |
|  | 2 | 5 | 0 | 6 | 2 | 0 | 2 | 13-7 | France | Geohydraulique | Prudhomme |
|  | 2 | 5 | 0 | 6 | 2 | 0 | 2 | 13-8 | France | " | Prudhomme |
|  | 2 | 5 | 1 | 6 | 5 | 2 | 2 | 13-9U | U.S. | Govt. | Prickett |
|  | 2 | 5 | 0 | 7 | 4 | 2 | 0 | 13-10 | Canada | Univ. | Chorley |
|  | 2 | 5 | 0 | 6 | 3 | 0 | 9 | 13-11 | U.S. | Univ. | Saleem |
|  | 2 | 5 | 0 | 7 | 1 | 0 | 2 | 13-12 | Netherlands | Govt. | Fillekes |
|  | 2 | 5 | 0 | 6 | 2 | 2 | 2 | 13-13U | Spain | Govt. | Gracia |
|  | 2 | 5 | 0 | 6 | 3 | 0 | 2 | 13-14 | France | Private | de Larminat |
|  | 3 | 5 | 0 | 6 | 1 | 0 | 2 | 13-15 | France | Govt. | Landel |
|  | 2 | 5 | 0 | 6 | 3 | 0 | 2 | 13-16 | U.K. | Geo. Sci. | Kitching |

## TABLE A-2b. SINGLE PHASE SATURATED FLOW: HYDRAULIC FLOW MODELS - MULTIPLE AQUIFER

| Purpose | Dynamics | Flow (Hydraulics) | Con-straints | Method | Documen-tation | Avail-ability | Past Appli-cations | Identification | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Model No. | Country | Institution | Reporter |
| Special | | | | | | | | | | | |
| | | 2 | 0 | 6 | 1 | 3 | 0 | 13-17 | Australia | Govt. | Seidel |
| | | 5 | 1 | 6 | 2 | 0 | 2 | 13-18 | Argentina | Govt. | Navarro |
| | 3 | 5 | 0 | 6 | 5 | 2 | 2 | 13-19 | U.S. | Battelle | Cole |
| | | 2 | 0 | 6 | 7 | 9 | 2 | 13-20 | U.S. | Private | Kleinecke |

## CODE SHEET FOR TABLE A-2a. & A-2b.

| Descriptor | Options | Code Number |
|---|---|---|
| Dynamics | Steady | 1 |
| | Nonsteady | 2 |
| | Both | 3 |
| Flow (Hydraulics) | Phreatic | 1 |
| | Phreatic + confined | 2 |
| | Phreatic + semiconfined | 3 |
| | Confined + semiconfined | 4 |
| | Phreatic, confined and semiconfined | 5 |
| | Confined | 6 |
| | Others or not specified | 9 |
| | None | 0 |
| Constraints | None | 0 |
| | Constraint present | 1 |
| Method | Numerical approximation of analytic solution | 1 |
| | Finite differences | 6 |
| | Finite elements | 7 |
| Documentation | Listing | 1 |
| | Listing + manual | 2 |
| | Listing + description or references | 3 |
| | Listing + manual + description | 4 |
| | Listing + manual + description + references | 5 |
| | Not existing | 6 |
| | Not specified | 7 |
| | Under development | 9 |
| Availability | Restricted | 1 |
| | Unrestricted | 2 |
| | Not available | 0 |
| | Unknown or not specified | 9 |
| | Available after publication | 3 |
| Past applications | Research | 1 |
| | Field problems | 2 |
| | None | 0 |
| | Unknown | 9 |

TABLE A-3a. SINGLE PHASE SATURATED FLOW: HYDRODYNAMIC FLOW MODELS - 2-Dimensional (continued)

| Purpose and/or Output | Process Flow Characteristics | Method | Documentation | Availability | Past Applications | Special Features | Identification | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Model No. | Country | Institution | Reporter (year) |
| Prediction of Head | Steady (phreatic, confined, possibly leaky) | F.E. | Complete | Yes | Field | hydraulic flow option, Boulton delayed yield, user oriented | 14-1U | U.S. | U.S.G.S. | Cooley (70) |
| | steady or nonsteady ( " ) | F.E. | Complete | Yes | Field | hydraulic flow option, nonlinear, user oriented | 14-2 | " | " | Cooley (74) |
| | " | F.D. | Complete | Yes | Field (many) | hydraulic flow option, evapotranspiration, storativity of aquitard, user oriented | 14-3 | " | " | Trescott (76) |
| Stream-Aquifer Interaction | Nonsteady, partially penetrating river | F.D. | References | ? | Field (1) | Constraints on river stage | 14-4 | " | Univ. of Missouri | Sharp (76) |
| | Nonsteady (phreatic and/or confined) | F.E. | ? | No | Evaluation of parameters (field) | free surface, two-level grids | 14-5 | France | BURGEAP | Clouet D'Orval (77) |
| Free Surface | Steady state (phreatic or confined) | F.E. | Complete | Yes | Field & Research (many) | seepage faces, flux through free surface, deformable grid, versatile, user oriented, option of axial symmetry | 14-6 | U.S. | Univ. of Calif. Berkeley | Neuman (69) |
| | Nonsteady (phreatic) | F.E. | Complete | Yes (guidance needed) | Little | time dependent boundaty conditions, deformable mesh, arbitrary anisotropy, user oriented, option of axial symmetry | 14-7 | " | " | Neuman (70) |

TABLE A-3a. SINGLE PHASE SATURATED FLOW: HYDRODYNAMIC FLOW MODELS - 2-Dimensional

| Purpose and/ or Output | Process Flow Characteristics | Method | Docu- ment- tation | Avail- abil- ity | Past Appli- cations | Special Features | Identification | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Model No. | Coun- try | Insti- tution | Reporter (year) |
| Free Surface | Steady or non-steady (phreatic) | F.E. | ? | No | some | arbitrary anisotropy, seepage boundary condition, option of axial symmetry | 14-8 | France | ARLAB | Blanc |
| Flow in the vicinity of a well | Steady or non-steady | F.D. | ? | No | Pumping test interpretation | automatic matching, axisymmetric | 14-9 | France | " | " |
| | Nonsteady (phreatic) | F.D. | ? | No | pump test analysis | storage of large diameter well, axisymmetric | 14-10 | France | BURGEAP | Clouet D'Orval (77) |
| | Nonsteady (phreatic or confined) | F.D. | Description & listing | No | Field: analyses of complex pumping tests | layered aquifer, axisymmetric, increasing time step | 14-11 | U.K. | Institute of Geol. Sciences | Kitching (76) |
| | Nonsteady (phreatic or confined and leaky) | F.D. | Description & listing | Yes | Field (many) (well losses, pumping rates) | multilayered, well losses, constraints on groundwater level and pumping rate, logarithmic mesh, small program, axisymmetric | 14-12 | U.K. | Univ. of Birmingham | Rushton (77) |
| Upconing of the interface under a pumping well | Nonsteady (phreatic) | F.E. | Complete | Yes | Field | Constraint on thickness of fresh water lense, saltwater under constant potential, nonuniform mesh size, anisotropy, local coordinates, axisymmetric | 14-13 | Canada | govt. Quebec | Sylvestre (73) |

TABLE A-3b. SINGLE PHASE SATURATED FLOW: HYDRODYNAMIC FLOW MODELS - 3-Dimensional

| Purpose | Flow Dynamics | | Method | Documentation | Availability | Past Applications | Special Features | Identification | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Steady | Nonsteady | | | | | | Model No. | Country | Institution | Reporter (year) |
| Prediction of Head | X | | F.E. | In progress | Yes | Field | Core and Mass Storage | 14-14 | Australia | Govt. | Wilsdon (76) |
| | X | X | F.E., F.D. | Not Specified | No | Field (some) | Free surface, flexible mesh size and configuration | 14-15<br>14-16<br>14-17 | France | ARLAB | Blanc |
| | X | X | F.D. | Listing manual | No | Field (many) | Free surface, user oriented | 14-18 | France | Govt. | Prudhomme (70) |
| | X | X | F.D. | ? | No | ? | Free surface, hierarchy of grids | 14-19 | France | BURGEAP | Clouet D'Orval (77) |
| | X | X | F.D. | Complete | Yes | Field (many) | Multilayered, storativity of aquitards, user oriented | 14-20 | U.S. | U.S.G.S. | Trescott (76) |
| Stream-aquifer Relationship | X | | F.E. | Poor | Yes | Field (little) | Versatile multilayered | 14-21 | U.S. | Govt. | Kuiper (76) |

TABLE A-4. SINGLE PHASE UNSATURATED FLOW MODELS

| Purpose and/or Output | Spatial Charac-teristics | System | Processes | Method | Documen-tation | Avail-ability | Past Applica-tions | Special Features | IDENTIFICATION | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Model No. | Country | Institution | Reporter (year) |
| Evapo-trans-piration satura-tion deficit | 1 dimen-sional (?) | Unsaturated zone, crop | Capillary flux, evapotrans-poration | Successive approxi-mation | In prepara-tion | No | Regional investiga-tion | Small storage (HP computer) | 15-1 | Netherlands | Govt. | van der Weert (76) |
| Water Content, capillary head, water balance | 2-dim. in vertical plane | homogeneous isotropic soil | irrigation evaporation, uptake by roots, flow | F. D. | Description (in French) | No | Research simulation of laboratory experiments (40 times) | Automatic time step, verifica-tion of analytic solutions, user oriented, large com-puter time | 15-2 | France | Govt. | Wolsack (72) |
| Water content, capillary head, | 1-dim., vertical | Irrigation ponds, multilayered unsaturated zone | Ponding, runoff, in-filtration, flow | Integrated Darcy equation for each layer | References listing | Yes | Not Specified | Constraint on minimal capillary head, user oriented | 15-3 | Netherlands | Govt. | Wind (73) |

TABLE A-5. SINGLE PHASE SATURATED-UNSATURATED FLOW MODELS (continued)

| | Spatial Characteristics | Flow | | Output | | | | | Method | Documentation | Availability | Past Applications | Special Features | Identification | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Dynamics | Hydraulics | H | Q | ψ | θ | ETP | | | | | | Model No. | Country | Institution | Reporter (year) |
| Hydraulic | 2d horizontal-saturated zone 1d vertical - unsaturated zone | Nonsteady | Phreatic & leaky | X | | | | X | F.E. | In Preparation | Not Specified | Field: effect of pumpage on drawdown, crop production and water balance. | Roots, evapotranspiration, land use, Hysteresis, user oriented | 16-1 | Nethl. | Govt. | Natl. Inst. Water Supply (75) |
| | | | | X | | X | X | X | | | | | | 16-2 | | | PJM de Laat (76) |
| | " | " | Phreatic, confined & leaky | X | | | | | F.D. | Complete | Yes | Field: response to river stage vegetation and pumpage | specific storativity, roots, river, aquitard, user oriented, mass storage | 16-3U | U.S. | USGS | Reed (74) |
| | " | " | Phreatic | X | | | | | F.D. | Complete | Yes | ? | Lumped unsaturated zone, flexible | 16-4 | U.S. | Auburn Univ. | Molz (74) |
| | " | " | " | X | X | | | | F.D. | Complete | No | Field: water supply to development | Land use, irrigation rules, constraints, lumped delayed vertical transfer function, flexible, error prediction for calibration, user oriented | 16-5 | France | SOGREAH | Barriere (75) |
| Hydrodynamic | 2 dimensional in vertical or horizontal plane | Nonsteady or Steady | Phreatic confined & leaky | X | X | X | X | | F.E. | In Preparation | After publication | None | Specific storativity, versatile, flexible, tested | 16-6 | U.S. | Univ. Berkeley | Narasimhan (75) |
| | " | Non-steady | Phreatic | X | X | X | X | X | F.E. | Complete | Yes | Research, Field: dam and reservoir design | Plants, evapotranspiration, seepage phases, user oriented | 16-7 | Israel | Govt. | Neuman (74) |
| | 2 dimensional in vertical plane | " | | X | | X | X | | F.E. | In Preparation | After Preparation | Field: Waste disposal sites Research: Flow to tile drains | Specific storativity, seepage phase, user oriented, arbitrary anisotropy | 16-8 | Canada | Univ. Waterloo | Pickens (75) |

TABLE A-5. SINGLE PHASE SATURATED-UNSATURATED FLOW MODELS

| | Spatial Characteristics | Flow | | Output | | | | | Method | Documentation | Availability | Past Applications | Special Features | Identification | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Dynamics | Hydraulics | H | q | ψ | θ | ETP | | | | | | Model No. | Country | Institution | Reporter (year) |
| Hydrodynamic | 2 dimensional in vertical plane | Non-steady | | X | | X | X | | F.E. | No | No | Research | Specific Storativity, seepage phase | 16-9 | U.S. | USGS | Cooley (74) |
| | " | " | | X | | X | X | | F.D. | Listing References | Yes | Research: infiltration and drainage | Maximum 5 different soil types, user oriented | 16-10 | U.S. | NM Tech. | Brutsaert (71) |
| | " | " | | X | X | X | X | | F.D. | Complete | Not Specified | Research: travel time through unsaturated zone | Homogeneous, isotropic, rigid aquifer | 16-11 | France | Inst.de Mecanique Grevoble | Vauclin (75) |
| | 3 dimensional | Steady and Non-steady | | X | | X | | | Integrated F.D. | Complete | Yes | None | Elastic or non-elastic deformation, hysteresis, versatile | 16-12 | U.S. | Univ. Berkeley | Narasimhan (75) |
| | " | " | | X | | X | | | F.E. | Complete | Yes | Field: flow in vicinity of a radioactive waste facility | Several unsaturated strata, specific storativity, arbitrary anisotropy, user oriented | 16-13U | Canada | Univ. Waterloo | Verge(75) |

List of symbols:
H - Piezometric head
Q - Discharge
ψ - Capillary head
θ - Water content
ETP - Evapotranspiration

TABLE A-6. SINGLE PHASE SUBSURFACE-SURFACE FLOW MODELS

| Subsurface | | | | Surface | | | | Method | Documentation | Availability | Past Applications | Special Features | IDENTIFICATION | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Elements | Spatial Characteristics | Process | Output | Elements | Spatial Characteristics | Process | Output | | | | | | Model No. | Country | Institution | Reporter (year) |
| Saturated and unsaturated zones | 3-dim. | Darcian nonsteady flow, any replenishment and exploitation | H,ψ,θ general | Stream connected to groundwater system | 1-dim. | Open Channel Flow (hydraulic) | Water depth, velocity | F.D. | Complete | Yes | Research. Field-once on an experimental water shed | No overland flow, storativity, soil moisture retension, versatile, large computer time and storage requirments | 17-1U | U.S. | IBM | Freeze (71) |
| Single-layered phreatic aquifer, springs, wells | 2-dim. horizontal | Nonsteady linear flow (hydraulic pumpage infiltration | H | River fed by springs | | Pumpage, artificial recharge seepage | Rate of Flow | F.D. for groundwater, accounting for river | Complete | No | Field (40 times) augmentation of river flow during droughts by pumping from groundwater | Storativity, impervious aquifer boundaries, constraint on head, small computer storage | 17-2 | U.K. | Govt. | Oakes (73) |
| Groundwater basin, phreatic or confined | 2-dim horizontal | Nonsteady linear or nonlinear (hydraulic) flow | H drawdown | River, lakes in direct contact with the aquifer | 1-dim. | Flow (hydraulic) | Depth, rate of flow | F.D. | Not specified | Yes | Field-impact of sewering Long Island, NY on groundwater levels and stream flow | Storativity, evapotransporation constraint on head, large data requirements | 17-3 | U.S. | Private | Chen (77) |
| Soil water zone, homogeneous isotropic aquifer | 1-dim. horizontal flow in vertical plane | Transfer through unsaturated zone, flow through aquifer (hydraulic) | H,θ | Reservoir | | Precipitation, evaporation drainage | | Analytic | Reference | ? | Field-evaluation of recharge | Linear transfer functions, specific, usable for calibration | 17-4 | France | Govt. | Degallier (72) |

List of symbols: H - Piezometric head

ψ - Capillary head

θ - Water content

TABLE A-7. MULTIPHASE FLOW MODELS

| Purpose and/or Output | Phases | Spatial Dimensions | Method | Documentation | Availability | Past Applications | Special Features | Identification | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Model No. | Country | Institution | Reporter |
| Head and/or position of interface between fresh and saltwater | Disjoint | 1 in vertical plane | F.D. | | Yes | Field | Dupuit assumption, small computer & storage | 18-1 | Israel | Univ. | Shamir |
| | | | " | Hebrew | ? | Field | Parabolic Interface | 18-2 | " | Tahal | Schwarz |
| | | | | Listing & public | ? | Field | multilayered aquifer, calibration & forecasting | 18-3 | " | " | Kapuler |
| | | 2 in vertical plane | Euler | Comments &description | Yes | Research | homogeneous, isotropic aquifer. Input: velocity | 18-4 | Netherlands | Univ. | Haitjema |
| | | | F.E. | ? | No | ? | | 18-5 | U.S. | Princeton U. | Pinder |
| | | | F.D. | ? | No | ? | free surface | 18-6 | France | BURGEAP | Clouet D'Orval |
| Head, flow net, interfaces | | 2 | Analytic functions | Complete | Yes | Field | general, little storage & data | 18-7U | Netherlands | | van der Veer |
| | | 2 or 3 | F.E. | Complete | ? | Field | variety of options steady & nonsteady | 18-8 | " | govt. | Barends |
| General | Joint | 2 vertical plane | F.E. | ? | No | ? | steady or nonsteady | 18-9 | U.S. | Princeton U. | Huyakorn |
| Flow of air and water around a pumping well | | | F.D. | No | No | Not yet | user oriented | 18-10 | U.S. | Univ. | Brutsaert |
| Gas & water flow Pressure & phase saturation | | 3 | F.D. | Complete | No | ? | 2 modifications: geothermal model, fractured matrix model. user oriented | 18-11 | U.S. | INTERCOMP | Lantz |

TABLE A-8. THE PRESENT STATUS OF SURVEYED FLOW MODELS

| | | | LUMPED | | | | DISTRIBUTED | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Ground water | | Ground and Surface Water | Hydrologic & non-hydrologic components | Single Phase | | | | | | | | | | | | | | | | Multiphase | | | | | | | | |
| | | | Single component | Multi component | | | Saturated | | | | | Satur.-Nonsaturated | | | | | Subsurface-Surface | | | | | | Subsurface | | | | | | | | Subsurface and Surface |
| | | | | | | | Hydraulic | | | Hydrodynamic | | Hydraulic | | | Hydrodynamic | | Hydraulic | | | | Hydrodynamic | | Disjoint | | | | Joint | | | | |
| | | | | | | | 1 | 2H | | 2V | 3 | 1 | 2H | | 2V | 3 | 1 | | 2H | | 2V | 3 | Hydraulic | | | | | | | | |
| | | | | | | | | Single Aquifer | Multiple Aquifer | | | | Single Aquifer | Multiple Aquifer | | | Single Aquifer | Multiple Aquifer | Single Aquifer | Multiple Aquifer | | | 1 | 2H | 2V | 3 | 1 | 2H | 2V | 3 | |
| DETERMINISTIC | Darcian Flow | Head | ①** | ①* | | | x | | | ③ | ① | | ① | | ① | ① | x | | | | | | | y | | | | | x | | |
| | | Stream-Aquifer | | | | | | x | x | x | x | | | | | | | | | x | | ①• | | | | | | | | | |
| | | Flow Pattern | | | | | | x | | | | | | | | | | | | | | | | x | ①+ | x | | | | | |
| | | Interface | | | | | | x | | ① | | | | | | | | | | | | | x | | x | | | | | | |
| | | Free Surface | | | | | | | | ① | | | | | | | | | | | | | | | | | | | | | |
| | | Well Flow | | | | | | | | x | | | | | | | | | | | | | | | | | | | x | | |
| | | Geothermal reservoir | | | | | | | | | | | | | | | | | | | | | | | | | | | | x | |
| | Non-Darcian Flow | Head | | | | | | x | | | | | | | | | | | | | | | | | | | | | | | |
| STOCHASTIC | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

*Documentation in French
**Documentation in Japanese

x Indicates existence of models
Circled numbers indicate number of usable models

•Applied only once
+ Valid for 2H and 2V

TABLE A-9. LUMPED MASS TRANSPORT MODELS

| Processes | | Hydrologic Elements | | Non-hydrologic Systems | Output | Documentation | Availability | Past Applications (problem) | Model Number | Country | Institution | Reporter (year) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mass Transport | Flow | Zone & Aquifer | Constituents | | | | | | | | | |
| Conservative | | | | | | | | | | | | |
| Complete mixing | Non-Steady | Aquifer connected to surface water | Single | | Concentration & Head | Listing and references | Yes (Listing) | Land application of sewage | 21-1 | U.S. | New Mex. Tech. & MIT | GELHAR & WILSON (74) |
| Complete mixing partial convection | Non-Steady | Saturated. Network of Aquifer comparments. | Single | Water Supply, Pumpage, Recharge<br>Irrigation<br>Import<br>Export | Total Salinity | No | No | Effect of water supply alternatives on groundwater quality (California) | 21-2 | U.S. | Govt. & Consult. | KLEINECKE (74) |
| Effective mixing depth | Steady | Aquifer and non-saturated zone | Multiple | Agriculture<br>Industry<br>Household<br>Reclamation | Concentration | (Hebrew) | No | Contamination trends due to waste water reuse under various operating rules | 21-3 | Israel | Tahal | Water Quality Section (75) |
| Nonconservative | | | | | | | | | | | | |
| Precipitation, dissolution and ion exchange | Steady | Saturated & unsaturated zone | Multiple | | Concentration | (Hebrew) | Yes | Changes in groundwater quality related to the carbonate system | 21-4 | Israel | Tahal | MERCADO (76) |
| Complete mixing Chemical equilibrium reactions, Precipitation, dissolution | Steady | Saturated & unsaturated zone surface water | Multiple | Agriculture (irrigated) | Concentration | Report & Listing | Yes | Effect of irrigation on surface & groundwater quality | 21-5 | U.S. | NM Tech | GELHAR (76) |

TABLE A-10a. DISTRIBUTED CONSERVATIVE MASS TRANSPORT MODELS - SINGLE HOMOGENEOUS PHASE

* + indicates an advantage
- indicates a difficulty

| Process | Hydrologic Zone | Spatial Dimensions | Method of Solution | Availability | Past Applications | Special Features* | IDENTIFICATION | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Model Number | Country | Institution | No. in Team | Reporter (year) |
| Immiscible (Convection) | Saturated | 2 horizontal | F.D. | Yes | Field | +User Oriented | 22-1 | U.S. | University | 2 | Sunada (77) |
| | | | " | No | Field | - Numerical dispersion<br>+ User Oriented | 22-2 | Israel | Tahal | 2 | Schwarz (72) |
| | Unsaturated | 1 Vertical | " | Limited Documentation | Research | Data | 22-3 | U.S. | University | 2 | Hanks (75) |
| Miscible (Convection & Dispersion) | Saturated | 3 | F.E | Yes | Field | -Stability under extreme conditions. +Multi-layered aquifer | 22-4 | U.S. | University | 3 | Gupta (75) |
| | | | | No | ? | +Special Equations Solver | 22-5 | U.S. | University | 2 | Pinder (74) |
| | | | | Limited | | | 22-6 | U.S. | University | 1 | Pinder (77) |
| | | 2 horizontal | " | No | Research | -Stability<br>-Computer time | 22-7 | France | University | 2 | Lessi (76) |
| | | | Characteristics | In Preparation | Field | +User Oriented<br>+Variety of sources & sinks (Point & areal) | 22-8 | U.S. | U.S.G.S. | 2 | Konikow (76) |
| | | | " | No | In test | + Correction for for local values | 22-9 | Israel | IBM - Tahal | | IBM (77) |
| | | | F.D.-Hybrid | Yes | Field | - Computer Time | 22-10 | Germany | University | 1 | Thiem (75) |
| | Sat-Unsat | 2 vertical | F.D. | In Preparation | | | 22-11 | U.S. | University | 1 | Shapiro (76) |
| | Sat-Unsat | 1 horiz. or vertical | F.E. | In Preparation | | | 22-12 | U.S. | University | 1 | Van Genuchten (76) |
| | Unsat. | 1 vertical | F.D. | No | Field | | 22-13 | Israel | Tahal | 1 | Kapuler (76) |
| | | | Characteristics | No | " | | 22-14 | U.K. | Water Research Center | 1 | Oakes (76) |

TABLE A-10b. DISTRIBUTED CONSERVATIVE MASS TRANSPORT MODELS - SINGLE NONHOMOGENEOUS PHASE

| Purpose and Output | System | Process | Spatial Dimensions | Method | Avail-ability | Past Applications | Identification | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Model No. | Country | Institution | No. in Team | Reporter Year |
| Sea water intrusion *P, C | Coastal aquifer, Single constituent | Convection and Dispersion | 2 dimens. in vertical plane | F.E. Block direct solution | Yes | ? | 22-15 | U.S. | Princeton University | 2 | SEGOL (74) |
| Movement of salt water interface towards a pumping well *P, C | Single well in confined aquifer, Single constituent | " | (axisymmetric) | " | Yes (limited) | ? | 22-16 | U.S. | " | 1 | HSIEH (76) |
| Quality of water pumped from a single well *P, C | Partially penetrating well in a confined vertically heterogeneous aquifer, Multiple constituents | Convection only + mixing in the well | " | F.D. 20 separate layers of a fixed chemical profile, moved vertically after each step | Not Documented | Field Project | 22-17 | U.S. | Illinois State Water Survey | 2 | PRICKETT (73) |

*P - pressure
C - concentration

TABLE A-11. DISTRIBUTED NONCONSERVATIVE MASS TRANSPORT MODELS - SINGLE HOMOGENEOUS PHASE (continued)

| Transport Mechanism | Constituents | Hydrologic Zone | Spatial Dimensions | REACTIONS | | | | Method of Solution | Availability | Past Applicats. | Special Features ** | Model Number | Country | Institution | No. in Team | Reporter (year) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Adsorption | Decay | Nitrogen | Other | | | | | | | | | |
| Immiscible (convection) | Single | Saturated | 2horizontal | X | | | | F.D. | No | Field (many) | +Hierarchical grid<br>-convergence under extreme conditions | 23-1 | France | Univ. | 5 | Ledoux (76) |
| | | Unsaturated | 1 vertical | X | X | | | " | No | Field | -length of time step | 29-2 | Israel | Tahal | | Avron (75) |
| Miscible (convection and dispersion) | Single | Sat.&unsat. | 3 | X | X | | | F.E. | Yes | None | +User oriented<br>-element size | 23-3 | Canada | Univ. | 1 | Segol (76) |
| | | Saturated | 3 | X | X | | | F.D. or characteristics | No | Field (many) | +User oriented<br>-convergence under extreme conditions | 23-4 | U.S. | Intera | | Lentz (75) |
| | | | 2 h or v | X* | X | | | F.E. | Yes | Field tests (3) | +User oriented<br>-stability | 23-5 | Canada | Univ. | 1 | Pickens (74) |
| | | | 2 | | X | | X | characteristics | ? | Research | | 23-6 | U.K. | ? | ? | Schwartz (Modeler)<br>Haimes (Reporter) (75) |
| | | | 1 h | X | | | | F.D. | ? | " | +adsorbed concentration<br>-Boundary conditions in extreme cases | 23-7 | France | Govt. | 3 | Brissaud (76) |
| | | Unsaturated | 2 v, 1 | X* | | | | " | ? | Research | +User oriented, quadratic adsorption | 23-8 | France | Govt. | 3 | Couchat (76) |
| | | " | 1 | | | | X | " | Yes | Research | -Stability and convergence, computer time | 23-9 | France | Univ. | 2 | Gaudet (77) |

TABLE A-11. DISTRIBUTED NONCONSERVATIVE MASS TRANSPORT MODELS - SINGLE HOMOGENEOUS PHASE

| Transport Mechanism | Constituents | Hydrologic Zone | Spatial Dimensions | REACTIONS |  |  |  | Method of Solution | Availability | Past Applicat. | Special Features ** | Model Number | Country | Institution | No. in Team | Reporter (year) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  | Adsorption | Decay | Nitrogen | Other |  |  |  |  |  |  |  |  |  |
| Miscible (convection and dispersion) | Multiple | Sat.&unsat. & perched | 2 h | X | X |  |  | F.D. | Yes | Field (1) (Waste disposal) | +variety of options<br>-stability, computer time | 23-10 | U.S. | U.S.G.S | 2 | Robertson (75) |
|  |  | Sat.&unsat. | 2 h or v and 3 | X | X |  | X | Random walk | Yes | Field | +User oriented<br>-computer time, stability | 23-11 | U.S. | Battelle | 3 | Ahlstrom (76) |
|  |  | Saturated | 1 | X | X |  |  | Analytical | Not Documented | Field (Waste disposal) | +User oriented<br>-precision | 23-12 | U.S. | Battelle | 2 | Burkholder (75) |
|  |  | " | 2 h | X | X |  |  | Characteristics | ? | " (many) | +variety of options<br>-extreme conditions | 23-13 | U.S. | U.S.G.S | 2 | Robertson (74) |
|  |  | " | " |  | X |  | X | F.D.orF.E. | Not Documented | Field (many) | -Time step, stability | 23-14 | U.S. | U.S.G.S | 1 | Grove (77) |
|  |  | " | 2 h or v | X |  |  | X | F.E. | No | None | +Hierarchy of grids<br>-stability | 23-15 | U.S. | Intercomp |  | Lantz (77) |
|  |  | Saturated or surface | 1 | X |  | X* | X | F.D. | Listing | Research | +generalized model, nonlinearity<br>-numerical dispersion | 23-16 | Israel | Govt. | 3 | Bachmat & Chetboun (76) |
|  |  | Unsaturated | 1 |  |  | X* | X | " | Yes | Research | +variety of options nonlinearity | 23-17 | U.S. | Univ. | 2 | Selim (76) |

*denotes nonlinearity option
** +indicates an advantage
-indicates a difficulty

## TABLE A-12. THE PRESENT STATUS OF SURVEYED MASS TRANSPORT MODELS

| STATISTICS | CHEMISTRY | | SPATIAL DIMENSIONS | SINGLE PHASE | | | | | | | | | | | | | | | | | | MULTIPHASE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | HOMOGENEOUS | | | | | | | | | | | | NONHOMOGENEOUS | | | | | | |
| | | | | Single Constituent | | | | | | MultiConstituent | | | | | | Single Constitu. | | | Multi Constitu. | | | |
| | | | | Immiscible | | | Miscible | | | Immiscible | | | Miscible | | | Immiscible | Misc-ible | | Immiscible | | | |
| | | | | Conser-vative | Nonconservative | | Conser-vative | Nonconservative | | Con-ser-va-tive | Nonconservat. | | Conser-vative | Nonconservative | | | Conserv. | Noncon-serv. | | Conserv | Non-conserv | |
| | | | | | Chem. | Biochem. | | Chem. | Biochem. | | Chem | Biochem. | | Chem. | Biochem. | | | | | | | |
| DETERMINISTIC | LINEAR | Equilibrium | (0D Lumped) | | | | 21-2<br>21-1 | | | | | | 21-3 *, u | 21-4<br>21-5 | | | | | | | | |
| | | | 1D | 22-3u | 23-2 u | | 23-13 u<br>22-12 *,u<br>22-14 u | 23-7S<br>23-9 u | | | | | | 23-12 | | | | | | | | |
| | | | 2D | 22-2 *<br>22-1 * | 23-1 * | | 22-8* 22-11*<br>22-7 22-9<br>22-6 22-10u | 23-5*<br>23-6 | | | | | | 23-13 23-11*u<br>23-10 23-15 *<br>*u 23-14* | | 22-17 | *<br>22-15<br>22-16 | | | | | |
| | | | 3D | | | | 22-5 S<br>22-4 S | 23-3 *, u | | | | | | | | | | | | | 23-4**<br>* | |
| | | Nonequ. | 0 | | | | | | | | | | | | | | | | | | | |
| | | | 1 | | | | | | | | | | | | | | | | | | | |
| | | | 2 | | | | | | | | | | | | | | | | | | | |
| | | | 3 | | | | | | | | | | | | | | | | | | | |
| | NON-LINEAR | Equilib. | 0 | | | | | | | | | | | | | | | | | | | |
| | | | 1 | | | | | | | | | | | | 23-16*, 23-17 u | | | | | | | |
| | | | 2 | | | | | 23-5*, 23-8 | | | | | | | | | | | | | | |
| | | | 3 | | | | | | | | | | | | | | | | | | | |
| | | Non-equ. | | | | | | | | | | | | | | | | | | | | |
| STO-CHASTIC | | | | | | | | | | | | | | | | | | | | | | |

u = unsaturated
s = saturated

Circled models are usable. Numbers indicate numbers of model reports

* Mass or heat transport in a deformable medium.
** Mass and heat transport model.

TABLE A-13. SUMMARY OF THE SURVEYED HEAT TRANSPORT MODELS (continued)

| Purpose and/ or Output | System | Processes | | Spatial Dimensions | Method | Documentation | Availability | Past Applications | Special Features | Identification | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Heat Transport | Flow | | | | | | | Model No. | Country | Institution | Reporter (year) |
| Evolution of water temperature in wells | Single aquifer, pumping wells. Time-varying heat source at the boundary. | Conservative, convection | | 2 Horizontal | F.D. | ? | No | ? | Computation of temperature on an externally given flow pattern. | 30-1 | France | BURGEAP | BURGEAP |
| | Single infinite homogeneous isotropic aquifer, natural uniform flow. Pumping and recharge wells. | | | " | Analytic | Complete (French) | No | Field (Many) | Head input. Mixing in wells. Output options of streamlines and temperature fronts. User oriented. | 30-2 | France | BRGM | Gringarten Landel (74) |
| | Single homogeneous confined aquifer, single injection - withdrawal well. | Conservative, convection and conduction | | 1 Horizontal radial | Analytic (approximate) | Internal Report | No | Field | Input: Front of heated water, injection - withdrawal schedule. Conduction at moving front and confining layers. User oriented input. | 30-3 | U. S. | G.E.-TEMPO | Hare (75) |
| Distribution of head and temperature of water (a) unsaturated zone | Rigid and homogeneous porous medium | " | Coupled with flow | 1 Vertical | F.D. | Reference (French) | Listing | Field | Connection with an atmospheric surface layer model. Interdependent flow and heat parameters. Time step dependent stability. | 30-4 | France | Institut de Mecanique | Vauclin (76) |

TABLE A-13. SUMMARY OF THE SURVEYED HEAT TRANSPORT MODELS

| Purpose and/ or Output | Systems | Processes | | Spatial Dimensions | Method | Documentation | Availability | Past Applications | Special Features | Identification | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Heat Transport | Flow | | | | | | | Model No. | Country | Institution | Reporter (year) |
| (b) saturated zone | Multilayered aquifer, wells | Conservative, convection and conduction | Non-coupled | 3 | F.D. | None | No | None | Steady state. Instability for extreme parameter contrasts. | 30-5 | France | Univ. de Bordeaux III | Cazal (77) |
| | Porous medium with double porosity: fractures & pores. | " | Coupled | 3 | F.E. | In preparation | After publication | None | Temperature and flow coupled through viscosity/Special solution scheme. Different velocity in pores & fractures. | 30-6 | U. S. | Yale Univ. | O'Neill (77) |
| | Heterogeneous isotropic, compressible porous medium. No sources or sinks. Conductive solid phase. Nonhomogeneous liquid. | " | Coupled | 1 or 2 or 3 | Integrated F.D. | Complete | Yes | Research & Field | Thermal equilibrium between solid & liquid. Numerical dispersion restricts step size. User oriented. | 30-7 | U. S. | U.S.G.S. | Sorey (74) |
| Pressure water content and temperature in a geothermal reservoir with (a) flow of steam | Stationary water. Flowing nonhomogeneous steam. | Non-conservative, convection and conduction | Coupled | 1 Vertical | F.D. | Open file report without operational instructions | Yes | None | Phase change, thermal equilibrium among phases. | 30-8 | U. S. | U.S.G.S. | Moench (76) |
| (b) joint flow of steam & water | Compressed water, two-phase mixtures. Superheated steam. | Conservative, convection and conduction | Coupled | 2 Horizontal | F.D., F.E. | Open-file report | Yes | Initial stage | Vertical heat leakage by conduction. Constraints on pressure range and saturation change. Possible conversion from single phase flow to 2-phase flow. User oriented. | 30-9 | U. S. | U.S.G.S. | Faust and Mercer (77) |

TABLE A-14. THE PRESENT STATUS OF HEAT TRANSPORT MODELS

| State Functions | | Flow Dimensions | Single Fluid Phase | | | | | | | Multiple Fluid Phases | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Uncoupled With Flow | | | | Coupled | | | Joint | | | | Disjoint |
| | | | | | | | | | | Un-Coupled | Coupled | | | |
| | | | Convective | | Convective and Conductive | | Convective | Convective and Conductive | | | Convective | Convective and Conductive | | |
| | | | Conservative | Nonconservative | Conservative | Nonconservative | | Conservative | Nonconservative | | | Conservative | Nonconservative | |
| Deterministic | Linear | 0 | | | | | | | | | | | | |
| | | 1 | | | 30-3S<br>50-3*** | | | 30-4U | 30-8S steam | | | 30-9S | | |
| | | 2H | 30-1S<br>30-2S | | | | | | | | | | | |
| | | 2V | | | | | | | | | | | | |
| | | 3 | | | 30-5S steady | | | 30-7S*<br>30-6S** | | | | | | |
| | Non-Linear | 1 | | | | | | | | | | | | |
| | | 2 | | | | | | 50-4*** | | | | | | |
| | | 3 | | | | | | | | | | | | |
| Stochastic | | | | | | | | | | | | | | |

* 1 or 2 or 3 Dimensional: Conducting Solid

** Double Porosity

A Circled Model is Usable.

*** Deformable Solid (Listed in TABLE 17)

TABLE A-15. DEFORMATION MODELS (continued)

| Purpose and Output | System Elements | Processes | | | Method | Documentation | Availability | Past Applications | Special Features | Identification | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Flow | Deformation of Porous Medium | | | | | | | | | | |
| | | Spatial Dim. & Flow Plane | Elastic | Non-Elastic | | | | | | Model No. | Country | Institution | Reporter (year) |
| **SUBSIDENCE** | | | | | | | | | | | | | |
| ΔH, ΔZ | Single Pumped Aquifer | 2 Horizontal | Uncoupled | | F.D. | References | Yes | Field | | 40-1 | U.S. | New Mexico Tech. | Gelhar (75) |
| H, ΔZ | 2Pumped & Recharged Aquifers. Deformable Aquitard | " | " | | F.D. | References (Japanese) | After publication | Field (many) | Storativity of aquitard. Hantush Leakage Function | 40-2 | Japan | company | Shibasaki (70) |
| H, ΔZ | Multiple Aquifer-Aquitard System | " | " | | F.E. | " | " | Field (many) | Storativity of aquitard | 40-3 | Japan | company | Shibasaki (76) |
| H, ΔZ | Multilayered Aquifer | 2 Vertical | " | | F.D. | " | " | Field (many) | Calibration Option | 40-4 | Japan | company | Shibasaki (72) |
| σ, ΔZ | Multiple Aquifer-Aquitard Series. Deformable Aquitards | 1 Vertical | Coupled | Coupled | F.D | References | After publication | Field | Pressure dependent permeability & storativity. Modified Terzagi theory for nonlinear response to loading and unloading. Input: Stress history. Calibration option | 40-5 | U.S. | USGS | Helm (71) |
| p, ΔZ | Saturated zone compressible groundwater | 3 | " | " | F.D. integrated | Manual & References | Yes | none | Nonlinear state functions. Stress dependent permeability & void ratio Arbitrary sources & sinks, General coordinates | 40-6 | U.S. | Univ. (Berkeley) | Narasimhan (76) |

TABLE A-15. DEFORMATION MODELS

| Purpose and Output | System Elements | Processes | | | Method | Documentation | Availability | Past Applications | Special Features | Identification | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Flow | Deformation of Porous Medium | | | | | | | | | | |
| | | Spatial Dim. & Flow Plane | Elastic | Non-Elastic | | | | | | Model No. | Country | Institution | Reporter (year) |
| SUBSIDENCE AND LATERAL DISPLACEMENT | | | | | | | | | | | | | |
| $p$, $\Delta Z$, $\Delta x$ | Saturated zone compressible fluid | 2 Vertical | Uncoupled | | F.E. | In preparation | After publication | Field | Biot's equations Linear state functions. Time varying loading | 40-7 | Netherlands | Univ. (Delft) | Verruijt (75) |
| $p$, $\Delta Z$, $\Delta r$ | Saturated zone | 2 Vertical | Uncoupled | Uncoupled | F.E. + Laplace Transform | ? | No | ? | Axisymmetric, Viscoelastic option | 40-8 | U.S. | Univ. (Princeton) | Safai (76) |

List of Symbols:

$H$ piezometric head

$\Delta H$ drawdown

$p$ pressure

$\sigma$ effective stress

$\Delta Z$ vertical displacement (compaction or expansion)

$\Delta x$, $\Delta r$ horizontal displacement (lateral or radial, respectively)

## TABLE A-16. THE PRESENT STATUS OF DEFORMATION MODELS

| State Functions | Flow Dimensions | | Saturated Zone | | | | | | | | | Saturated-Unsaturated Zones |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Single Fluid Phase | | | | | | | | Multiple Phases | |
| | | | Subsidence | | | | Subsidence And Lateral Displacement | | | | | |
| | | | | | | | 2 Dimensional | | | 3 Dimensional | | |
| | | | Elastic | | Nonelastic | | Elastic | | Nonelastic | | | |
| | | | Un-Coupled | Coupled | Un-Coupled | Coupled | Un-Coupled | Coupled | | | | |
| Linear | 1 | | | 40-5 | | 40-5 | | | | | | |
| | 2H | Single Aquifer | 40-1 | | | | | | | | | |
| | | Multiple Aquifer | 40-2<br>40-3 | | | | | | | | | |
| | 2V | | 40-4 | | | | 40-7<br>40-8 | | | | | |
| | 3 | | | | | | | | | | | |
| Nonlinear | 1 | | | | | | | | | | | |
| | 2 | | | | | | | | | | | |
| | 3 | | | 40-6 | | 40-6 | | | | | | |

TABLE A-17. OTHER PREDICTION MODELS

| PURPOSE AND/OR OUTPUT | SPATIAL DIMENSIONS AND PLANE | HYDROLOGIC SYSTEM |  |  | PROCESSES |  |  |  | METHOD | DOCUMENTATION | AVAILABILITY | PAST APPLICATIONS | Special Features | Identification |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | ZONES | AQUIFERS | PHASES | FLOW | DEFORMATION | MASS TRANSPORT | HEAT TRANSPORT |  |  |  |  |  | Model No. | Country | Institution | Reporter (Year) |
| Solving subsurface flow and transport equations | 2 or 3 |  |  |  |  |  |  |  | General F.E. scheme completed with a block iterative equation solver. | Complete (?) | Yes | ? | General purpose code for solving transient nonlinear partial differential equations in one or two dependent variables | 50-1 | U.S. | Princeton University | Pinder (76) |
| Concentration of a constituent or temperature | 2 | Saturated-Unsaturated | Deformable | Homogeneous Fluid |  | X | Convection, Diffusion, Dispersion, First order decay and sorption | X | F.E. | Listing and Reference | Yes | None | General purpose code to simulate steady or transient noncouservative heat or mass transport in a variably saturated deformable porous medium for a given velocity field. Adaptable to various computers. Numerical dispersion in highly convective problems. | 50-2 | U.S. | Rockwell Hanford Operations (Company) | Baca (77) |
| Pressure and temperature in accumulating sediments | 1 D Vertical | Saturated |  | Fluid, Solid |  | Compaction of Sediments |  | Conduction, Dispersion, Forced convection | F.D. | Complete (thesis) | Yes (?) | Field (once) |  | 50-3 | U.S. | University of Missouri | Sharp (74) |
| Pressure and temperature in a liquid dominated geothermal reservoir | 3 D | " | Deformable porous matrix | Single phase compressible fluid | Steady or nonsteady | Vertical compaction (elastic or nonelastic) |  | Conduction, convection | Integrated F.D., accelerated iterative scheme | Complete | Yes | None | Arbitrary heterogeneity, isotropy. Nonlinear state functions. Coupled flow, heat and deformation. Automatic adjustment of time step. | 50-4 | U.S. | University of California | Narasimhan (76) |
| Pressure, contaminant concentration and temperature in a heterogeneous aquifer | 3 D | " | Heterogeneous confined aquifer | Single fluid | Nonsteady |  | Convection, Dispersion, radioactive decal, adsorption, desorption | Forced & natural convection, dispersion, conduction | F.D., linear successive over-relaxation or direct inversion | Complete | Yes | ? | Source-sink terms, single solute, concentration and temperature dependent density and viscosity, new option of N constituents, first order reactions, pressure effects on enthalpy. User-oriented. | 50-5 | U.S. | INTERA | Lantz (75) |
| Frost propagation and frost heaving in a water saturated porous medium | 1 D | " | Multilayered Homogeneous isotropic aquifer | Water Ice Solid | Of water only |  |  | Conduction | F.D. iterative, computation of temperature followed by displacement of frost line | Complete (?) | Yes | Field (Road design) | Phase change, transient, free surface, front line (Stefan's problem) conditional stability. User oriented. | 50-6U | France | Lab. Central des Ponts and Chaussees | Service de Mathematiques (75) |

TABLE A-18. THE PRESENT STATUS OF PREDICTION MODELS

| Statistics | Mathematics | Process | Single Phase | | | | | | | | | | | | | | | | | | | | | | | | | Multiphase | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Homogeneous | | | | | | | | | | | | | | | | | Nonhomogeneous | | | | | | | | Homogeneous | | | | | | Nonhomogeneous |
| | | | Conservative | | | | | | | | | Nonconservative | | | | | | | | Conservative | | | | | Nonconserv. | | | Disjoint | | | Joint | | | |
| | | | Saturated | | | Sat. - Unsat. | | | Sub. - Sur. | | | Saturated | | | Sat. - Unsat. | | | Sub.-Sur. | | Saturated | | | Sat. Un-Sat. | Sub. Sur. | Subsurf. | | Sur. Sub. | Sat | Sat. Un-Sat. | Sur Sub | Sat. | Sat. Un-Sat. | Sur. Sub | |
| | | | Lumped | HDL | HDN | Lumped | HDL | HDN | Lumped | HDL | HDN | Lumped | HDL | HDN | Lumped | HDL | HDN | Lumped | Distri. | Lumped | HDL | HDN | | | Lumped | Distri. | | | | | | | | |
| Deterministic | Linear | Flow | x | x | x | | x | x | | x | x | | | | | | | | | | | | | | | | | 18-7u<br>18-5<br>x | | | 18-9<br>18-11<br>x | | | |
| | | Mass Transport | | x | x | x | x | x | | | | x | x | x | x | x | x | x | | | | 22-15<br>22-16<br>x | | | | | | | | | | | | |
| | | Heat Transport | | x | x | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | Deformation | | x | x | | | | | | | | | | | 50-2<br>x | | | | | | | | | | | | | | | | | | |
| | | Heat & Deformation | | x | x | | | | | | | | | | | 50-2<br>x | | | | | | | | | | | | | | | | | | |
| | | Mass & Deformation | | | | | | | | | | | | | | | | | | | | | | | | 50-5<br>x | | | | | | | | |
| | | Mass & Heat | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | Mass, Heat & Deformation | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | Nonlinear | Flow | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | Deformation | | | 40-6<br>x | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | Mass Transport | | | | | | | | | | | 23-16<br>23-5u<br>x | | | | | | | | | | | | | | | | | | | | | |
| Stochastic | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

Abbreviations: HDL - Hydraulic  Sat. - Saturated  Sur., Surf. - Surface
HDN - Hydrodynamic  Unsat. - Unsaturated  Sub. - Subsurface

Numbers are Model Numbers.

TABLE A-19. GROUNDWATER MANAGEMENT MODELS: QUANTITY (continued)

| Purpose | System | | State Variables | Decision Variables | Constraints | | | Objective Function | Method | Documentation | Availability | Past Applications | Special Features | Identification | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Hydrologic | Technologic | | | State | Decision | Others | | | | | | | Model Number | Country | Institution | Modeler |
| Distribution of pumpage under given rules | Aquifer Cells | | Salinity. Water Level Depth of Seawater Intrusion | Pumpage. Lacking Capacity of pumpage and conveyance | Level of state variables | Operational rules | Total Pumpage (Output from a Lumped Model) | | Operational Algorithm | Description (Hebrew) | No | Field: Planning of pumpage distribution | Operational rules depend on priority levels of demand and critical levels of hydrologic monitors. Policy matrix corresponding to the above. Single time step operation. Conjunctive with simulation model. | 61-1 | Israel | Tahal | Schwartz(73) |
| Optimal location and operation of wells | Single Aquifer 2D | | None | Well location<br>Pumping rate<br>Head | | Head (Lower Bound) | Total net pumpage | Sum of heads at node points at each time interval | L.P. | References | Yes | Field (once) Feasibility Study | Simulation within optimization framework. Physical Objective. Solution at each interval used as initial condition for next interval. Static option. | 61-2 | U.S. | Stanford Univ. | Alley *<br>Aguado (76)<br>Remson |
| " | Aquifer (Homogeneous or Heterogeneous) | | Head or Drawdown in well | Well location<br>Pumping rate | Drawdown | | Total pumpage | Cost | Simulation and curve fitting | Referencu + Dissertation (Bostock) | Yes | Hypothetical Examples | Uncertainty in estimating hydraulic conductivity of heterogeneous aquifer. No specific Algorithm for curve fitting. Cost includes construction, replacement, energy and water deficit. Dynamic | 61-3 | U.S. | Univ. of Arizona | Bostock *<br>Simpson (77)<br>Roeffs |
| " | Aquifer 2D or 3D | Water supply system | Head | " | | Pumping rate, depth, diameter | " | Cost | L.P. | ? | ? | ? | Cost includes Drilling, pumps and surface network. Conjunctive simulation and optimization. Static. | 61-4 | France | Arlab | Baradat<br>Blanc |
| " | Aquifer 2D | | Head | " | Head (Lower bound) | Pumping capacity (upper bound) | " | Discounted operating cost (concave) | Concave programming, upper linear constraints (TUI Method) | ? | ? | Hypothetical Case | Discounted operating cost only. Dynamic planning model formulated as a discrete time control problem. | 61-5 | U.S. | Cornell Univ. | Willis<br>Newman (77) |
| Optimal operation of a well field | Single or Multiple Aquifer 2D | | Head. Drawdown | Pumping rate | Drawdown | | | Linear combination of pumping rates | L.P. | Complete | Yes | Field | Influence coefficients computed by simulation as input to optimization. Programmer oriented. | 61-6U | France | Ecole de Mines | Levassor (75) |

*Reported by Haimes and Das.

TABLE A-19. GROUNDWATER MANAGEMENT MODELS: QUANTITY

| Purpose | System |  | State Variables | Decision Variables | Constraints |  |  | Objective Function | Method | Documentation | Availability | Past Applications | Special Features | Identification |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | Hydrologic | Technologic |  |  | State | Decision | Others |  |  |  |  |  |  | Model Number | Country | Institution | Modeler (year) |
| Optimal Operation of a well field | Groundwater 2D Linear | Water Supply | Drawdown or Head | Semi-Annual Pumping Pattern |  | Well-pumping capacities | Total Pumpage | Cost | Simulation (F.D.) & Optimization - Q.P. | ? | ? | Hypothetical Case | ATF which relates pumpage (or Recharge) to Drawdown at locations where pumpage (or Recharge) are Decision Variables. Dynamic. | 61-7 | U.S. | U.S.G.S. | Maddock* (72) |
| Optimal Mining of A Basin | Groundwater Basin 2D Linear | Pumping Wells, Farms (Irrigated) | Water Level | Pumping rate in each time step Irrigated Acreage of crops | Water Level below which wells are excluded | Acreage of crops |  | NET Benefit for Each farm (Annual)<br>Net Benefit for Entire Basin (Long Term) | Simulation followed by L.P. at each time point | Reference | Yes | Research | Steady Recharge. Evapotranspiration. Crop Production Function. Depth-dependent water cost. | 61-8 | U.S. | U.S.G.S. | Bredehoeft Young (72) |
| Optimal Cropping and Pumping Pattern | Single Aquifer Linear | Irrigated Farm Wells | Drawdown | Pumpage, Acreage of Crops | Drawdown, acreage | Consumptive use of crops |  | Net Benefit from Farming | Simulation (response functions) followed by Q. P. | No | No | Model was developed for Research only | Regret Function as a measure of Economic loss given an incorrect decision because of errors in parameter estimation. In combination with Bayesian Decision Technique this function is used to rank data by priority for further data collection. Dynamic. Large storage requirement. | 61-9 | U.S. | U.S.G.S. | Maddock (73) |
| Economic Incentives for Efficient Groundwater Management | " | Water Supply, Irrigated Farms | Drawdown | Pumpage, Drawdown, Acreage, Taxation and Rebate Rates | Drawdown | Acreage minimum water requir., pumping capacity |  | Net Revenue (2 levels) Basinwide & Each Farm | Decomposition Optimization by Q.P. | References Report | Yes | Hypothetical Case | Algebraic Technological Function. Quotas, Taxes, and Rebates. Pumpage below the Quota entitles to a Rebate, Pumpage above the Quota is Taxed. Each Year Taxes are redistributed among users with zero accumulation. Multilevel Optimization and Coordination. LaGrange Multiplier as cost or savings per unit digression from quota. Dynamic. | 61-10 | U.S. | U.S.G.S. | Maddock* and Haimes (75) |

*Reported by Haimes & Das

TABLE A-20. GROUNDWATER MANAGEMENT MODELS: QUALITY AND QUANTITY

| Purpose | System | | State variables | Decision variables | Constraints | | | Objective Function | Method | Documentation | Availability | Past Applications | Special Features | Identification | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Hydrologic | Technologic | | | State | Decision | Others | | | | | | | Model No. | Country | Institution | Modeler (year) |
| Groundwater Supply and Salinity Control | Aquifer Underlying Irrigation District IB | Irrigation Supply | Groundwater Storage Salinity | Capital for construction and Equipment. Water for Leaching. Water for Irrigation | Salinity Storage | Pumping Capacity | | Discounted Net Benefit Associated with Water Use and Salinity | Nonlinear Programing (Lagrangian Formulation) | Reference | ? | ? | Analytical framework for an integrated approach to the Water Use-Salinity Problem. Dynamic. | 62-1 | U.S. | University of Rhode Island | Cummings* McFarland (74) |
| Waste Water Disposal Through Wells As A Component Of A Regional Waste Treatment System | Groundwater. Waste water. Imported water | Injection Wells | Head concentration of Pollutants | Water Quality standard for each Pollutant. Volume of Dilution Water of known Quality. Waste water to injection wells. | | Water Quality Level. Capacity of Injection wells | | Total Cost (including removal by surface Treatment & Importation of Dilution water | Simulation, Mixed Integer Programing | Reference | ? | Hypothetical case | The saturated zone as a component of a Regional Waste Treatment System including Waste Water Treatment Plant and External Sources of Dilution water.<br>Given injection rates through wells and pumping pattern. Two-Dimensional Steady Flow and Mass Transport Equations | 62-2 | U.S. | Cornell University | Willis* (76) |
| Waste Water Disposal Coupled with Supply | Groundwater, Non-conservative Pollutants | Waste Disposal in Groundwater. Waste water reclamation | Head, Pollutant concentrations | Surface treatment level before injection. Waste load distribution to Injection wells. Head and concentration in wells. Pumpage distribution. | Maximum concentrations | Capacity of wells | Water supply demands.<br>Total waste discharge | Minimum cost (including cost of pumpage, waste injection and surface treatment) | Simulation (finite elements), Two-stage Optimization (by Concave Programing): (1) Optimal Pumping and Waste Injection (Quantity Aspect) (2) Optimal Surface Treatment (Quality Aspect) | Reference | ? | Once with Field Data | Optimization model for conjunctive long range Management of Groundwater Quantity and Quality taking into consideration the assimilative capacity of a Groundwater basin. Operational policy for a Multi-component Pollutant system including well injection, surface treatment, and water supply. Mass Transport by Dispersion and Convection. Non-convex problem. Dynamic | 62-3 | U.S. | Cornell University | Willis* (73) |

Reproduced from best available copy.

* Reported by Haimes and Das.

TABLE A-21a. CONJUNCTIVE GROUNDWATER AND SURFACE WATER MANAGEMENT MODELS: QUANTITY - LUMPED MODELS

| Purpose | System |  | State variables | Statistics | Decision variables | Constraints |  |  | Objective Function | Method | Documentation | Availability | Past Applications | Special Features | Identification |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | Hydrologic | Technologic |  |  |  | State | Decision | Others |  |  |  |  |  |  | Model No. | Country | Institution | Modeler (year) |
| Policy planning - Development and Operation | Groundwater & surface water basins | Supply, use and production | Storage. Level of development | Stochastic replenishment | Capacities Recharge Withdrawal Water Allocation | storage & capacity | allocation Development |  | Expected discounted net benefit | Stochastic D.P. | Complete (Hebrew) Reference (English) | yes | Field | Part of an integrated planning scheme. Loss due to deficit in supply, compensation for cutback in allocation. Salvage value. Multiple sources and users. **p.d. of state & objective | 63-1U | Israel | Tahal | Schwarz (74) |
|  | " | " | Storage | Stochastic input and demand | Pumpage Reservoir site |  | Site of facilities, supply | Demand | Expected cost of supply | Iterative L.P. | Listing and Description | yes | Research | Given demand. Nonlinear pumping cost. Linear decision rule. Chance constraints. Random parameters | 63-2 | U.S. | New Mexico Tech | Gelhar (76) |
| Policy planning - Operation | " | " |  | Stocastic replenishment and streamflow | Pumpage. Import. Allocation | storage & capacity | Pumping rate |  | Expected discounted net benefit | Stochastic D.P. | None | no | Field (once) | Value - iterative method for Markov chain. **p.d. of state & objective function. | 63-3 | U.S. | Montana State Univ. | Burt (62) |
|  | " | " | Storage | Stochastic recharge | Pumpage Allocation |  | ? |  | " | " | Not specified | unknown | Field (once) | Quadratic benefit function. Interaction between all sources of water | 63-4 | U.S. | Univ. Illinois | Saleem (69) |
|  | " | " | " | Deterministic | Pumpage & recharge | capacity | Level of supply by higher models | Operating rules | Net benefit | Two: (a)Monte Carlo simulation (b)Monte Carlo linear programming | Hebrew | no | Field (many) Mostly simulation | Synthetic input produced by Monte Carlo methods. Part of an integrated planning scheme | 63-5 | Israel | Tahal | Gablinger (73) |
|  | Groundwater surface water imported water |  |  | " | Source of supply |  |  | Demand | Minimum Cost | Out of kilter algorithm | Report | yes | Case study (example) | Network analysis as a screening tool for alternative water supply patterns and structures in a multisource and multiuser system. Shadow prices | 63-6 | U.S. | Univ. Illinois | Hamdan * Meredith (75) |
| Policy planning - Operation and pricing |  | Supply and use | Available water | Deterministic | Pumpage Price of water | supply | price |  | Net benefit | Segmential unconstrained minimization | ? | ? | Research | Multiple sources. Relationship between demand, supply and price.<br>* Reported by Haimes and Das<br>** P.d. - Probability density | 63-7 | U.S. | UCLA | Mobasheri* Grant (72) |

TABLE A-21b. CONJUNCTIVE GROUNDWATER AND SURFACE WATER MANAGEMENT MODELS: QUANTITY - DISTRIBUTED MODELS (continued)

|  | System |  |  |  | Constraints |  |  |  |  |  |  |  |  | Identification |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Purpose | Hydrologic | Technologic | State variables | Decision variables | State | Decision | Others | Objective Function | Method | Documentation | Availability | Past Application | Special Features | Model Number | Country | Institution | Modeler (year) |
| Operation of A Stream-Aquifer System under given rules | Interconnected Aquifer & Stream Evapotranspiration | Wells, Canals, Reservoirs, Irrigation | Storage | Pumpage, Surface Water Delivery to Canals. Reservoir Operation | Capacities | Operational Rules | Prior Appropriation. Interstate Compacts. Demand | Mean Annual Value & Standard Deviation of Supply | Simulation & Accounting | None |  | Simulations of Water Management Alternatives in River Valleys (Many) | Response Functions. Operational Rules. Programmer Oriented. Dynamic. | 63-8 | U.S. | U.S.G.S. | Taylor Luckey (73) |
| Optimal Water allocation for agriculture from a stream aquifer system | Coupled 2D Groundwater and Stream Flow | Irrigated Agriculture | Stream Flow | Pumpage, Recharge, Downstream supply, Acreage of crops |  | Surface Water for Irrigation | Maximum Acreage Pumping Capacity, Down-Stream flow, Water rights | Net Benefit From Agriculture | Simulation & L.P. | Reference | Yes | Yield (once) | Static and dynamic options. Two Linear Programming Routines. One determines Cropping Pattern. The other allocates available water. Optimal solution not guaranteed as input to optimization is obtained from simulation, instead of simultaneous coupling of the two. | 63-9 | U.S. | Resources for future U.S.G.S. | Young Bredehoeft (72) |
| Optimal Operation of a Stream-Aquifer System under Stochastic Demands | Coupled 2D Groundwater & Stream flow | Irrigated Agriculture | Groundwater level Stream flow | Stream withdrawal, Groundwater pumpage & recharge, Return flow to stream |  | Transfer from Stream to Aquifer. Reuse | Rights. Satisfaction of expected Demand | Expected Total Discounted Operating Cost | Simulation & Q. P. | Reference | Yes | ? | Algebraic Technological Function from Groundwater Simulation. Minimum cost Management Rule. Sensitivity of Discounted expected cost and Operating Rule to the Variation in Parameter Value. Stochastic demand and Drawdown. | 63-10 | U.S. | U.S.G.S. | Maddock* (74) |
| Maximization of yield from a water resource system | Ground Water-2D, Surface Water, Imported Water |  | Ground Water Levels or their Gradients | Pumpage | Drawdown | Pumping capacity, Annual Pumpage | Minimum Supply, Availability of imported Water | Total Pumpage over Planning Period | L.P. | ? | ? | Example | Linear System. Influence Coefficients which are evaluated only for times and location of interest. Maximization of yield as an adequate objective for planning long term Aquifer exploitation when no constraints on budget and demands are considered. | 63-11 | Israel | TAHAL | Schwarts* (73) |

*reported by Haimes & Das

TABLE A-21b. CONJUNCTIVE GROUNDWATER AND SURFACE WATER MANAGEMENT MODELS: QUANTITY - DISTRIBUTED MODELS

| Purpose | System | | State variables | Decision variables | Constraints | | | Objective Function | Method | Documentation | Availability | Past Application | Special Features | Identification | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Hydrologic | Technologic | | | State | Decision | Others | | | | | | | Model Number | Country | Institution | Modeler (year) |
| Optimal Operation of Limited Regional Water Resources by a Decentralized Management System | Groundwater Surface water Linear 2D | Agriculture & Industrial - municipal Water Supply | Head | Regional Authority Decisions: Inter-subregional Boundary Water Levels; Artificial Recharge in Subregions. Pumping Tax Rate. Local Agency Decisions: Flows across Subregional Boundaries Pumpage in Subregion, Import | Water Level, Pumping Capacity | Imported Water, Capacity of recharge Facility. Zero Flow Inter-subregional Boundary Condition | Artificial Recharge Cost Must Equal Tax Revenue. Demand (?) | Cost of Water Supply | Decomposition. Simulation, Iterative Two-Level Optimization, Iterative Coordination | ? | ? | Hypothetical Case | Coordinated Planning Methodology for a Decentralized Water Management in a region Water Supply administered by several Local Agencies, each controlling the development and Operation within a subregion, except for inter-subregional Boundary Conditions, Artificial Recharge Rate and Pumping Tax Rate which are controlled by a Regional Authority. The Tax Revenue is spent on an Artificial Recharge Facility for the Region. Decomposition provides for Independent Optimization of each Local Agency's cost Function which is not released to the Regional Authority. Computational efficiency needs improvement. | 63-12 | U.S. | Case Western Reserve Univ. | Yu<br>Haimes<br>(74) |
| Optimal Operation of a large scale System | Multi-Aquifer System Coupled with Multi-Stream System. 2D, Linear | Multiple Users | Groundwater Head. Streamflow Rate | Groundwater Pumpage. Surface water withdrawal. Artificial Surface water Recharge | Drawdown | Pumping Capacity. Recharge Capacity. Surface water withdrawal | Minimum Demand. Penalty for Depleting Surface Stream | Discounted net Benefit | Decomposition Simulation Optimization Reduced Gradient Coordination | Complete | Yes | Field: Once | Methodolgy for Analyzing a Complex Water Resource System. Algebraic Technological Function for a Multi-Aquifer System. Stream-Aquifer Response Functions. Hierarchy of Simulation Models. Iterative Coordination.<br>Convergence of Hierarchical Coordination Scheme not guaranteed. Computational limitations due to high dimensionality. User oriented. | 63-13 | U.S.<br>"<br>Israel<br>Venezuela<br>"<br>" | Univ.<br>"<br>Company<br>Univ.<br>"<br>" | Haimes<br>Das<br>Draizin<br>Garey<br>Sarkar<br>Beconegra<br>(76) |

TABLE A-22. CONJUNCTIVE GROUNDWATER AND SURFACE WATER MANAGEMENT MODELS: QUALITY AND QUANTITY

| Purpose | System | | State variables | Statistics | Decision variables | | | | Constraints | | | Objective Function | Method | Documentation | Availability | Past Applications | Special Features | Identification | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Hydrologic | Technologic | | | Development | Operation | Allocation | Economics | State | Decision | Others | | | | | | | Model Number | Country | Institution | Modeler (Year) |
| Wastewater Treatment & Water Supply | groundwater & surface water + waste water. Lumped | Supply, use, production treatment | Quantity and quality (chemical& biological) | Deterministic | | Pumpage Level of treatment | Source of Supply | | Desired quality& quantity | | | Slack between desired and reached levels of state variables | Mixed integer programming | In French | no | test (once) | Screening model for managing little watershed. Static. Multiple sources and users. Multiple choices of sources and treatment levels. Bivalent integer variables. Solution by standard packages. Calibration of economic parameters. | 64-1 | France | Ecole de Mines de Paris | Hubert (76) |
| Wastewater Treatment & Water Supply | | | As above plus thermal | " | Water works | Mode of supply | " | | Quantity & quality of water supply | | Reliability level | Slack between planned policy & implementation | Linear programming | In French | no | Planning of river basin management | Lumped. Multiple users sources and modes of supply. Screening model for managing large watershed. | 64-2 | France | Ecole de Mines de Paris | Hubert (76) |
| Groundwater Supply and Salinity Control | Groundwater, 2D, Surface water, Imported water | Agricultural Production. Irrigation. | Groundwater Salinity | | | Ground water Pumpage, Surface water Withdrawal, Water Transport | Water import | | Salinity of Irrigation Drainage | | Irrigation Demand | Cost | Optimization of Salt Transport by L.P. Followed by Detailed Simulation (Characteristics) | Reference | | Once on A Field Case | Salt Transport by Convection and Dispersion Least Cost Combination of Distributing Groundwater and Surface Water over the Basin within prescribed Salinity and Irrigation Requirements. Ground and Surface Waters not Connected. | 64-3 | U.S. | Colorado State University & University of California | Helweg Labadie (76) |

Reproduced from best available copy.

TABLE A-23. THE PRESENT STATUS OF MANAGEMENT MODELS

| Management Aspects | | | | | Hydrologic System | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Single Phase | | | | | | | | | | | | | Multi-phase |
| | | | | | Homogeneous | | | | | | | | | | | | Non-ho-mogeneous | |
| | | | | | Conservative | | | | | | | Nonconservative | | | | | | |
| | | | | | Saturated Zone | | | Satu-rated-Unsatu-rated | Subsurface & Surface | | | Saturated Zone | | | Satu-rated-Unsatu-rated | Sub-surface & Surface | | |
| | | | | | | Distributed | | | | Distributed | | | Distributed | | | | | |
| Number & Kind of Manage-ment Objectives | Number of Manage-ment Levels | Area | Task | Decisions | Lumped | Hydrau-lic | Hydro-dynamic | | Lumped | Hydrau-lic | Hydro-dynamic | Lumped | Hydrau-lic | Hydro-dynamic | | | | |
| Single (Physical or Economic) | Single | Water Quantity | Supply | Development | | P 61-2<br>C 61-3<br>C 61-5 | C 61-4$^1$ | | B63-1$^3$<br>63-2$^3$ | | | | | | | | | |
| | | | | Operation | | 61-1$^4$<br>CP 61-6<br>C 61-7 | | | B63-3$^3$<br>B63-4$^3$<br>B63-5<br>C63-6 | 63-8$^3$<br>P63-11<br>C63-10$^3$ | | | | | | | | |
| | | | | Operation & Production | | B 61-8<br>B 61-9 | | | | B63-9$^2$ | | | | | | | | |
| | | | | Operation & Economics | | | | | B63-7 | | | | | | | | | |
| | | Water Quality & Quantity | Salinity Control | Development | | | | | | | | | | | | | | |
| | | | | Operation | | | | | | | | | | | | | | |
| | | | | Operation & Economics | | B 62-1 | | | | C64-3 | | | | | | | | |
| | | | Waste water Disposal | Development | | | | | | | | | | | | | | |
| | | | | Operation | | C 62-2$^1$ | | | | | | | | | | | | |
| | | | | Engineering & Economics | | | | | | | | | | | | | | |
| | | | Waste Water Disposal and Water Supply | Development | | | | | P64-2 | | | | | | | | | |
| | | | | Operation | | | | | P64-1$^1$ | | | | C62-3$^5$ | | | | | |
| | | | | Engineering & Economics | | | | | | | | | | | | | | |
| | | | Environ-mental Protection | | | | | | | | | | | | | | | |
| | Multiple | Quantity | Supply | Development | | | | | | | | | | | | | | |
| | | | | Operation | | | | | | B63-11 | | | | | | | | |
| | | | | Operation & Economics | | | | | | C63-12 | | | | | | | | |
| | | | | Oper., Prod. & Economics | | B 61-10 | | | | | | | | | | | | |
| | | Quality & Quantity | | | | | | | | | | | | | | | | |
| Multiple | | | | | | | | | | | | | | | | | | |

Objective function: P-physical; B-benefit; C-cost
EP-economic or physical

1-static; 2-static & dynamic; 3-stochastic; 4-accounting; 5-multicomponent surface treatment
Oper.-operation
Prod.-production

Circled models are usable

TABLE A-24a. IDENTIFICATION MODELS - DIRECT CALIBRATION (continued)

| System (Model calibrated) | Spatial Detail | Output |  |  |  |  | Objective Function | Constraints on Output | Method of Calibration |  | Documentation | Availability | Past Applications | Special Features and Comments | Identification |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | K | T | S | Sources and sink terms | Others |  |  | Non-iterative | Iterative |  |  |  |  | Model No. | Country | Institution | Reporter (year) |
| Distributed Transient Hydraulic Flow Model with given past records of water levels, and other input data | 2-Horizontal |  | Scalar or Tensor | X |  |  | Weighted, including $\Sigma (\Delta U)^2$, $\Delta T$ & $(\Delta S)$ |  | Least squares |  | Complete Spanish | No | Field | Spline interpolation of head over time. Polygonal mesh. Large core storage. | 70-1 | Argentina (U.N.) | Govt. | Navarro (73) |
|  | " |  | Scalar | X |  |  | Various options on $(\Delta U)$ and $(\Delta U)^2$ | X | L.P.<br>Q.P. |  | ? | ? | Research | Sensitive to minor input errors. Needs further development before use. | 70-2 | Israel | Govt. | Nefos (72) |
|  | " |  | Tensor | X | X |  | $\Sigma (\Delta U)^2$ |  | N.L.P. |  | ? | Yes | Field (once) | Spline functions estimate piezometric surface from discrete data. Nonconvex problem. More research needed to improve the method. | 70-3 | U.S. | University of Arizona | Sagar (73) |
|  | " | Scalar |  |  |  |  | Error between computed and given K at a point on a streamtube |  |  | Numerical integration of the Boussinesq equation for K along streamtube | Complete | ? | Field (two sites) | Flexible output and display. Small core storage. Uniform storativity. Neglected source terms. Need for conductivity values along a reference line intersecting the streamlines. Solution for data at one time point. | 70-4 | U.S. | Battelle | Friedrichs (75) |
|  | " (complex domain) |  | Scalar | X |  |  | $\Sigma (\Delta H)^2$ | X |  | Numerical solution of the well function for T and S by optimization | Complete | Yes | Field | Magnitude of problem reduced by decomposition into homogeneous regions, with impervious boundaries each enclosing a single well. Solution by optimization at two levels: direct search and Gauss Seidel. | 70-5 | U.S. | University of Case Western | Haimes (67) |
| Distributed Nonsteady Flow Model Single Aquifer | 2-Horizontal |  | One per each side of cell | X | X |  | $\Sigma (\Delta U)^2$ | X |  | Q.P. with special iterative algorithm | Under development | No | Field | Small amount of core storage by correcting the parameters of the cells successively in a given iteration. Proof of convergence. Applicable to a large number of cells. Data stored on a mass storage device. | 70-6 | Israel | Govt. | Dax (76) |

TABLE A-24a. IDENTIFICATION MODELS - DIRECT CALIBRATION

| System (Model calibrated) | Spatial Detail | Output | | | | | Objective Function | Constraints on Output | Method of Calibration | | Documentation | Availability | Past Applications | Special Features and Comments | Identification | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | K | T | S | Sources and sink terms | Others | | | Non-iterative | Iterative | | | | | Model No. | Country | Institution | Reporter (year) |
| Set of wells with given past records of pumpage and drawdown | given distances between wells | | | | | Coefficients of a power series response function relating drawdown to pumpage | $\Sigma\ (\Delta s)^2$ | X | Stepwise regression | | Nonexistent | No | Being tested in the field | No pumping and drawdown records should be missing for sites where drawdown is to be predicted. Presently expanded to include missing data and ungauged sites | 70-7 | U.S. | U.S.G.S. | Maddock (76) |
| | Indices of wells | | | | | Lumped parameters relating drawdown to pumpage | $\Sigma\ (\Delta s)^2$ | X | | Decomposition gradient search | ? | ? | Research | Surrogate parameter approach. Superposition of drawdown in wells | 70-8 | U.S. | Colorado State University | Labadie (75) |
| Blackbox system with observed time series of input and output undergoing a linear and stationary process | Lumped | | | | | Impulse response functions | Sum of weighted squares of deviations between predicted and observed output | X | Deconvolution | | Complete | Yes | Field . | Deconvolution (determination of the impulse response of an input-output system. Applicable to a complex system or to parts of it. Modification for nonlinear and nonstationary systems. User oriented. Proved convergence. Shape and and smoothness of response function not always satisfactory. | 70-9 | France | Govt. | de Marsily (69) |

TABLE A-24b. IDENTIFICATION MODELS - INDIRECT CALIBRATION (continued)

| System (Model calibrated) | Spatial Detail | Output | | | | | Objective Function | Constraints on Output | Method of Calibration | | Documentation | Availability | Past Applications | Special Features and Comments | Identification | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | K | T | S | Sources and sink terms | Others | | | Trial and Error | Iterative Search | | | | | Model No. | Country | Institution | Reporter (year) |
| Salt conservative closed groundwater basin in contact with surface water basin, given past records related to water and salt balances | 2-Horizontal | Scalar | | | X | | Difference between measured and calculated heads, conductivity and salt content | | X | | Not specified | Unknown | Unknown | Steady state approximation. (combination of a direct solution as a first estimate with corrections involving simulation) | 70-10 | Canada | Govt. | Wallick (76) |
| Distributed steady hydraulic groundwater flow model | " | | Scalar | | | | Difference between computed and observed water levels | | ? | | Listing only | No | Field | No indication of the parameter adjustment technique and of the objective function | 70-11 | U.K. | Govt. | Aldrick (74) |
| Distributed nonsteady hydraulic flow model | " | Scalar | | X | X | | $\Sigma\ (\Delta H)^2$ | | | Gradient | Description and references | Unknown | Unknown | Main difficulty: sufficiently accurate input state, especially pumping rates | 70-12 | U.S. | Texas Tech. University | Knowles (73) |
| Two interconnected coastal aquifer columns | Lumped | Vertical | | X | X | Initial interface elevation | $\Sigma\ (\Delta H)^2$ | | | Gradient (binary search technique) | No | No | Field (many) | Small number of variables, adequate for first insight into aquifer performance. Only the techniques can be transferred. | 70-13 | U.S. | G.E. TEMPO | Kleinecke (74) |

TABLE A-24b. IDENTIFICATION MODELS - INDIRECT CALIBRATION

| System (Model calibrated) | Spatial Detail | Output | | | | | Objective Function | Constraints on Output | Method of Calibration | | Documentation | Avail-ability | Past Applications | Special Features and Comments | Identification | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | K | T | S | Sources and sink terms | Others | | | Trial and Error | Iterative Search | | | | | Model No. | Country | Institution | Reporter (year) |
| Distributed nonsteady hydraulic flow model | 2-Horizontal | | Scalar as a second order polynomial function of position | | | Coefficients of the T polynomial | $\Sigma (\Delta H)^2$ | X | | Marquardt's nonlinear estimation | Complete | Yes | Field | Includes two phases: identification and validation. Finite difference simulation model. Convergence and rate of convergence depend on initial guess of parameter values. Convergence to global minimum cannot be assured. User-oriented. | 70-14 | U.S. | Case University | Haimes (73) |
| " | " | | Scalar | X | X | | Difference between computed and observed water levels & flow directions | X | | Special gradient method | | | Field (5 sites) | Sensitivity analysis. Large computer time. | 70-15 | Germany | University Hannover | Boehm (75) |
| As above, but steady | - | Tensor | | | X | Statistics of parameters and heads | $\Sigma (\Delta H)^2$ | | | Accelerated combination of quasi-linearization, and Gauss-Newton method | In preparation | Not Yet | Research (with field data) | Under development. Transmissivity option. Finite element simulation model. The two acceleration parameters must sometimes be adjusted for convergence. Standard error and correlation matrix of parameters. User oriented. | 70-16 | U.S. | U.S.G.S. | Cooley |

Reproduced from best available copy.

## IDENTIFICATION MODELS

### List of Symbols

K - Hydraulic conductivity

T - Transmissivity

S - Storativity

$\Sigma$ - Summation symbol

$\Delta(\ )$ - Error in Quantity enclosed in the brackets

U - Volume

H - Head

S - Drawdown

L.P. - Linear Programming

Q.P. - Quadratic Programming

N.L.P. - Nonlinear Programming

TABLE A-25. THE PRESENT STATUS OF IDENTIFICATION MODELS

| Method | | Constraints | Single Phase | | | | | | | Multi-Phase |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Homogeneous | | | | | | Non-Homogeneous | |
| | | | Conservative | | | | | Non-Conservative | | |
| | | | Lumped | Distributed | | Saturated-Un-Saturated | Subsurface and Surface | | | |
| | | | | Hydraulic | Hydrodynamic | | | | | |
| Direct | Non-Iterative | Unconstrained | | 70-1 | | | | | | |
| | | Constrained | 70-9 | 70-2<br>70-3<br>70-7 | | | | | | |
| | Iterative | Unconstrained | | 70-4 | | | | | | |
| | | Constrained | | 70-5<br>70-8<br>70-6 | | | | | | |
| In-Direct | Trial and Error | | | 70-10<br>70-11 | | | | | | |
| | Iterative Search | Unconstrained | 70-13 | 70-12 | | | | | | |
| | | Constrained | | 70-14<br>70-15<br>70-16 | | | | | | |

TABLE A-26. DATA MANIPULATION MODELS

| Purpose | System | Processes | Method | Documentation | Availability | Past Applications | Special Features | Identification | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Model No. | Country | Institution | Reporter (year) |
| Accounting of exogenous inflow to a groundwater basin | Groundwater basin, surface waters, water agencies, water users. | Inflows, outflows, transfers. | Water balance | none | no | Field (many) | Specialized to Kern County, California | 80-1 | U.S. | private | Kleinecke<br>(76) |
| Account of deep percolation as input to a ground water flow model | Soils, crops, irrigation units surface water. | Evapotranspiration rainfall, return flow, pumping, deep percolation | Volume balance | Complete (report) | Restricted | Field | Limited to areas with sufficient data on water use. Prepares input for flow models. User oriented. | 80-2 | Argentina | UNDP | Navarro<br>(69) |
| Error detection in ground water levels. | Time series of observations in wells | | Decomposition of time series into components & their estimations | Description (Hebrew) | Yes | Field | Deviations from expected value as index of acceptability. Each site treated separately. Need for extension to multivariate time series. | 80-3 | Israel | govt. | Ben-Zvi<br>(76) |
| Regionalization of point sample data and assessment of estimate precision. | Point sample data as realization of a spatial stochastic process. | | Optimal interpolation by "Kriging" | Complete | Yes | Field (many) | Unbiased estimator as a weighted average of the data. Standard deviation of the error. Package of 90 subroutines. Variety of output. Can be coupled to a plotter. User oriented. | 80-4 | France | govt. | Delhomme<br>(75) |
| Data retrieval and model input. | Well data base. Aquifer data. | Data retrieval. Data input from contour maps. | | Complete | After publication | Field | Special applications and manipulations. Preparation and check of model inputs. Interactive graphics scope. Variety of output. User oriented. Small core storage. Mass storage. | 80-5 | U.S. | Battelle | Friedrichs<br>(77) |

# APPENDIX B

## LIST OF MODELERS

This list includes the names and addresses of all modelers who worked on the models surveyed in this study. In each case only the name of the reporter of the model is listed on the associated Table.

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| ADAMS, B.R. | Institute of Geological Sciences<br>Exhibition Road<br>London SW7<br>United Kingdom | 12-20 | A-2a |
| AGUADO | Stanford University<br>Palo Alto, California 94305 | 61- 2 | A-19<br>A-23 |
| AHLSTROM, S. | Battelle, Pacific Northwest Laboratories<br>Water and Land Resources Department<br>P.O. Box 999<br>Richland, WA 99352<br>(509) 946-2121 | 23-11<br>80- 5 | A-11<br>A-12<br>A-26 |
| ALDRICK, R.J. | Directorate of Resource Planning<br>Yorkshire Water Authority<br>21 Park Square South<br>Leeds LS1 2QG<br>United Kingdom | 70-11<br>12-31 | A-24b<br>A-25<br>A-2a |
| ALLEY, W.M. | Stanford University<br>Palo Alto, California 94305 | 61- 2 | A-19<br>A-23 |
| ASHKENAZI, S. | TAHAL Consulting Engineers, Ltd.<br>54 IBN Gvirol Street<br>Tel-Aviv, Israel | 12-55 | A-2a |
| ASHLEY, R.P. | Sir M. MacDonald & Partners<br>Demeter House<br>Station House<br>Cambridge, CB1 2RS<br>United Kingdom | 12- 9 | A-2a |
| AVRON, M. | TAHAL Consulting Engineers<br>54 IBN Gvirol Street<br>Tel-Aviv, Israel | 23- 2 | A-11<br>A-12 |
| BACA, R. | Rockwell Hanford Operations<br>P.O. Box 250<br>Richland, WA 99352 | 50- 2 | A-17<br>A-18 |
| BACHMAT, Y. | Hydrological Service of Israel<br>P.O. Box 6381<br>Jerusalem, Israel | 23-16<br>70- 6 | A-11<br>A-12<br>A-24a |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| BAKR, A. | New Mexico Institute of Mining and Technology<br>Campus Station<br>Socorro, NM 87801 | 21- 5 | A-9<br>A-12 |
| BARADAT, Y. | ARLAB<br>Eau et Environment<br>Sophia Antipolis - Boite Postale 15<br>06560 Valbonne - Alpes Maritimes<br>France | 12-19<br>12-22<br>12-62<br>61- 4 | A-2a<br>A-2a<br>A-2a<br>A-19<br>A-23 |
| BARENDS, F. | Laboratory of Soil Mechanics<br>Stieltjesweg, Delft<br>The Netherlands | 18-8 | A-7 |
| BARRIERE, P. | SOGREAH<br>74, avenue Marie Reynoard<br>38100 - Grenoble<br>France | 16- 5 | A-5 |
| BARTOLOME, J.C. | Gabinete de Calculo<br>Ministerio de Obras Publicas<br>Nuevos Ministerios, Madrid<br>Spain | 13-13u | A-2b |
| BASTIN, G. | Laboratory of Automatics and System Analysis<br>University of Louvain<br>1348 Louvain-la-Neuve<br>Belgium | 12-32 | A-2a |
| BAZIER, G. | Dept. of Agricultural Engineering<br>University of Louvain<br>1348 Louvain-la-Neuve<br>Belgium | 12-32 | A-2a |
| BEAR, J. | TECHNION<br>Dept. of Civil Engineering<br>Technion-Israel<br>Institute of Technology<br>Haifa<br>Israel | 12-14<br>70- 2 | A-2a<br>A-24a<br>A-25 |
| BECONEGRA, C. | No Address<br>Contact Y.Y. Haimes | 63-13 | A-21b<br>A-23 |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| BEDINGER, M.S. | U.S. Geological Survey<br>Water Resources Division<br>Box 25046, Mail Stop 406<br>Denver Federal Center<br>Lakewood, CO 80225 | 16- 3u<br>12-44u | A-5<br>A-2a |
| BEN-ZVI, M. | Hydrological Service<br>P.O. Box 6381<br>Jerusalem<br>Israel | 80- 3 | A-26 |
| BEZES, C. | Laboratoire de Geologie<br>C.E.R.G.H. - U.S.T.L.<br>Place Eugene Bataillon<br>34060 Montpellier Cedex<br>France | 11- 2 | A-1 |
| BIBBY, R. | Water Research Centre<br>P.O. Box 16, Henley Road<br>Medmenham Laboratories<br>Medmenham, Marlow<br>Buckinghamshire SL7 2HD<br>United Kingdom | 12- 8 | A-2a |
| BIESEL, F. | GEOHYDRAULIQUE<br>10, rue Eugene Renault<br>94700 Maisons - Alfort<br>France | 13- 7<br>13- 8<br>14- 8 | A-2b<br>A-2b<br>A-3b |
| BLANC, G. | ARLAB<br>Eau et Environment<br>Sophia Antipolis - Boite Postale 15<br>06560 Valbonne - Alpes Maritimes<br>France | 12-19<br>14-19<br>14-15<br>12-25<br>14- 8<br>14-16<br>14-17<br>12-22<br>61- 4 | A-2a<br>A-3a<br>A-3b<br>A-2a<br>A-3a<br>A-3b<br>A-3b<br>A-2a<br>A-19<br>A-23 |
| BLANK, D. | TAHAL Consulting Engineers, Ltd.<br>54 IBN Gvirol Street<br>Tel-Aviv<br>Israel | 12-48<br>22- 2 | A-2a<br>A-10a<br>A-12 |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| BOEHM, B. | Institut fur Wasserwirtschaft<br>Hydrologie und Landw. Wasserbau<br>Technische Universitat Hannover<br>Callinstr. 15 c, 3000 Hannover<br>F.R. Germany | 70-15 | A-24b<br>A-25 |
| BONNIER, A. | SCET - INTERNATIONAL<br>5-7, rue Bellini<br>92806 - Puteaux<br>France | 12- 2 | A-2a |
| BOSTOCK, C.A. | Department of Hydrology<br>University of Arizona<br>Tucson, Arizona 85721 | 61- 3 | A-19<br>A-23 |
| BREDEHOEFT, J. | U.S. Geological Survey<br>Mail Stop 413<br>12201 Sunrise Valley Drive<br>Reston, VA 22092<br>(703) 860-6971 | 22- 8<br><br>63- 9<br><br>61- 8 | A-10a<br>A-12<br>A-21b<br>A-23<br>A-19<br>A-23 |
| BRESLER, E. | Dept. of Soil Physics<br>The Volcani Center A.R.O.<br>Bet Dagan<br>Israel | 16- 7 | A-5 |
| BRIECHLE, D. | Institut fur Wasserwirtschaft<br>Hydrologie und landwirtschaftlichen Wasserbau<br>Technische Universitat Hannover<br>Callinstre. 15 c, 3000 Hannover 1<br>F.R. Germany | 12-26 | A-2a |
| BRISSAUD, F. | Service de Radioagronomie<br>C.E.N. de Cadarache<br>13115 - St. Paul lex Durance<br>France | 23- 7 | A-11<br>A-12 |
| BRUTSAERT, W. | Dept. of Civil Engineering<br>458 Aubert Hall<br>University of Maine<br>Orono, Maine 04473<br>(207) 581-7693 | 12-38<br>16-10<br>18-10 | A-2a<br>A-5<br>A-7 |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| BRYAN, C.A. | University of Montana<br>Missoula, MT 59801 | 12-30u | A-2a |
| BURKHOLDER, H.C. | Battelle, Pacific Northwest Laboratories<br>Water and Land Resources Department<br>P.O. Box 999<br>Richland, WA 99352 | 23-12 | A-11<br>A-12 |
| BURT, O. | Dept. of Economics<br>Montana State University<br>Bozeman, MT 59715<br>(406) 994-3701 | 63- 3 | A-21a<br>A-23 |
| BURT, W.W. | Dept. of Civil Engineering<br>Colorado State University<br>Fort Collins, CO 80523 | 12-47 | A-2a |
| CARRIERE, A. | GERSAR<br>B.P. 4001<br>3001 - Nimes<br>France | 13- 6 | A-2b |
| CAZAL, A. | Institut de Geodynamique<br>Universite de Bordeaux III<br>Avenue des Facultes<br>33405 - Talence<br>France | 30- 5<br><br>12-23 | A-13<br>A-14<br>A-2a |
| CEARLOCK, D.B. | Battelle, Pacific Northwest Laboratories<br>Water and Land Resources Department<br>P.O. Box 999<br>Richland, WA 99352 | 70- 4 | A-24a<br>A-25 |
| CHAN, P. | Box 1751 G.P.O.<br>Adelaide 5001<br>South Australia | 12-41 | A-2a |
| CHEN, C.W. | Tetra Tech, Inc.<br>Environmental Systems Engineering<br>3700 Mt. Diablo Boulevard<br>Lafayette, CA 94549 | 17- 3 | A-6 |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| CHETBOUN, G. | Hydrological Service<br>P.O. Box 6381<br>Jerusalem<br>Israel | 23-16 | A-11<br>A-12 |
| CHIDLEY, T. | Dept. of Civil Engineering<br>University of Aston<br>Gosta Green<br>Birmingham<br>United Kingdom | 12-27 | A-2a |
| CHILES, J.P. | Ecole Nationale Superieure des Mines de Paris<br>Centre de Geostatistique<br>35, rue Saint - Honore<br>77305 - Fontainebleau<br>France | 80- 4 | A-26 |
| CHORLEY, D.W. | Dept. of Earth Sciences<br>University of Waterloo<br>Waterloo, Ontario<br>Canada | 13-10 | A-2b |
| CLABORN, B.J. | High Plains Underground Water Conservation District #1<br>Lubbock, TX 79409 | 12-34<br>70-12 | A-2a<br>A-24b<br>A-25 |
| CLOUET D'ORVAL, M. | BURGEAP<br>70, rue Mademoiselle<br>75015 Paris<br>France | 13- 3<br>18- 6<br>14-19<br>14- 5<br>14-10 | A-2b<br>A-7<br>A-3b<br>A-3a<br>A-3a |
| COLE, C.R. | Battelle, Pacific Northwest Laboratories<br>Water and Land Resources Department<br>P.O. Box 999<br>Richland, WA 99352 | 22- 5<br>13-19<br>12-30u<br>12-59 | A-10a<br>A-12<br>A-2b<br>A-2a<br>A-2a |
| COLVILLE, J.S. | CSIRO<br>Division of Soils<br>Private Bag No. 2<br>Glen Osmond, S.A. 5064<br>Australia | 12-35<br>12-36 | A-2a<br>A-2a |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| COOLEY, R. | U.S. Geological Survey<br>Box 25046, Mail Stop 415<br>Denver Federal Center<br>Lakewood, CO 80225 | 14- 2<br>14- 1u<br>16- 9<br>70-16 | A-3a<br>A-3a<br>A-5<br>A-24b<br>A-25 |
| COUCHAT, P. | Service de Radioagronomie<br>C.E.N. Cadarache<br>13115-Saint Paul lez Durance<br>France | 23- 7<br><br>23- 8 | A-11<br>A-12<br>A-11<br>A-12 |
| CUMMINGS, R.G. | The University of Rhode Island<br>Warwick, Rhode Island 02886 | 62- 1 | A-20<br>A-23 |
| DAGAN, G. | Dept. of Engineering<br>University of Tel-Aviv<br>Israel | 18- 1 | A-7 |
| DAS, P. | School of Civil Engineering<br>Purdue University<br>West Lafayette, IN 47907 | 70-14u<br><br>63-13 | A-24b<br>A-25<br>A-21b<br>A-23 |
| DAVIDSON, J.M. | Soil Science Department<br>University of Florida<br>Gainesville, FL 32611 | 23-17 | A-11<br>A-12 |
| DAVIS, J. | Water Research Centre<br>P.O. Box 16, Henley Road<br>Medmenham Laboratories<br>Medmenham Marlow<br>Buckinghamshire SL7 2HD<br>United Kingdom | 12-15 | A-2a |
| DAX, A. | Hydrological Service<br>P.O. Box 6381<br>Jerusalem, Israel | 70- 6 | A-24a<br>A-25 |
| DE BACKER, L. | Dept. of Agricultural Engineering<br>University of Louvain<br>1348 Louvain-la-Neuve<br>Belgium | 12-32 | A-2a |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| DEGALLIER, R. | Bureau of Geological and<br>Mineral Research (BRGM)<br>Department of Hydrology<br>B.P. 6009<br>45018 - Orleans Cedex<br>France | 17- 4 | A-6 |
| DE LAAT, P.J.M. | International Institute for<br>Hydraulic & Environmental<br>Engineering<br>Delft<br>The Netherlands | 16- 2 | A-5 |
| DE LARMINAT, R. | SOGREAH<br>47, Avenue Marie Reynoard<br>38100 - Grenoble<br>France | 13-14 | A-2b |
| DELFINER, P. | Ecole Nationale Superieure<br>des Mines de Paris<br>35, rue Saint-Honore<br>77305 Fontainebleau<br>France | 80- 4 | A-26 |
| DELHOMME, J.P. | Ecole Nationale Superieure<br>des Mines de Paris<br>Centre de Geostatistique<br>Centre d'Informatique Geologique<br>35, rue Saint-Honore<br>77305 - Fontainebleau<br>France | 80- 4 | A-26 |
| DE MARSILY, G. | Ecole Nationale Superieure<br>des Mines de Paris<br>35, rue Saint-Honore<br>77305 Fontainebleau<br>France | 70- 9 | A-24a<br>A-25 |
| DEMIER, W.V. | Battelle, Pacific Northwest<br>Laboratories<br>Systems Department<br>Richland, WA 99352 | 12-30u | A-2a |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| DRACUP, J. | Dept. of Civil Engineering<br>7620 B Boelter Hall<br>University of California<br>Los Angeles, CA 90024<br>(213) 825-1906 | 70- 5 | A-24a<br>A-25 |
| DREIZIN, J. | Mekorof Water Company<br>Nine Lincoln Street<br>Tel-Aviv<br>Israel | 70-14a | A-24b<br>A-25 |
| | | 63-13 | A-21b<br>A-23 |
| DREYFUS, A. | Centre d'Informatique Geologique<br>Ecole des Mines de Paris<br>35, rue Saint-Honore<br>77305, Fontainebleau<br>France | 64- 2 | A-22<br>A-23 |
| DUJARDIN, J.M. | SOGREAH<br>47, avenue Marie Reynoard<br>38100 - Grenoble<br>France | 13-14 | A-2b |
| ECKHARDT, J.E. | Dept. of Civil Engineering<br>Colorado State University<br>Fort Collins, CO 80721 | 12-46 | A-2a |
| EWING, L. | General Electric - TEMPO<br>P.O. Drawer QQ<br>Santa Barbara, CA 93102 | 70-13 | A-24b<br>A-25 |
| FAUST, C.R. | U.S. Geological Survey<br>Mail Stop 413<br>12201 Sunrise Valley Drive<br>Reston, VA 22092 | 30- 9 | A-13<br>A-14 |
| FEDDES, R.A. | Institute of Soil and Water<br>Agriculture Research Organization<br>Bet Dagan<br>Israel | 16- 7 | A-5 |
| FILLEKES, W. | National Institute for Water Supply<br>P.O. Box 150<br>Leidschendam<br>The Netherlands | 13- 5 | A-2b |
| | | 13-12 | A-2b |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| FLORES, W. | New Mexico Institute of Mining and Technology<br>Campus Station<br>Socorro, NM 87801 | 63- 2 | A-21a<br>A-23 |
| FOOTE, H.P. | Battelle, Pacific Northwest Laboratories<br>Water & Land Resources Department<br>P.O. Box 999<br>Richland, WA 99352 | 23-11 | A-11<br>A-12 |
| FREEZE, R.A. | Dept. of Geological Sciences<br>University of British Columbia<br>2075 Westbrook Place<br>Vancouver, B.C. V6T 1W5<br>Canada | 17-1u | A-6 |
| FRIEDRICHS, D.R. | Battelle, Pacific Northwest Laboratories<br>Water and Land Resources Department<br>P.O. Box 999<br>Richland, WA 99352 | 80- 5<br>12-59<br>70- 4 | A-26<br>A-2a<br>A-24a<br>A-25 |
| FRIND, E. | Dept. of Earth Sciences<br>University of Waterloo<br>Waterloo, Ontario N2L 3G1<br>Canada<br>(519) 855-1211 x 3959 | 12- 6<br>13-10<br>16-13u<br>23- 3<br><br>14-13 | A-2a<br>A-2b<br>A-5<br>A-11<br>A-12<br>A-3a |
| FUJISAKI, K. | Kokusai Aerial Surveys, Co., LTD<br>Asahigaoka 3, Hino<br>Tokyo 191<br>Japan | 40- 3 | A-15<br>A-16 |
| FURUNO, K. | Chiba Prefectural Research Institute for Environmental Pollution (CRIEP)<br>Inage-Kaigan 3-5, Chiba 281<br>Japan | 40- 4 | A-15<br>A-16 |
| GABLINGER, M. | TAHAL Consulting Engineers, Ltd.<br>54 IBN Gvirol Street<br>Tel-Aviv<br>Israel | 63- 5 | A-21a<br>A-23 |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| GAILLARD, P. | SOGREAH<br>47, avenue Marie Reynoard<br>38100 - Grenoble<br>France | 13-14 | A-2b |
| | | 16- 5 | A-5 |
| GARAY, H.L. | Dept. de Ingerieria de Sistemas<br>Faciltad de Ingenerha<br>Universidad de Los Andes<br>Merida<br>Venezuela | 70-14u | A-24b<br>A-25 |
| | | 63-13 | A-21b<br>A-23 |
| GARCIA, L.L. | INTECSA<br>Internacional de Ingenieria Y Estudios Tecnicos, S.A.<br>Condesa de Venadito, 1<br>Madrid<br>Spain | 13-13u | A-2b |
| GAUDET, J.P. | Institut de Mecanique de Grenoble<br>B.P. 53 - Centre de Tri<br>38041 - Grenoble Cedex<br>France | 23- 9 | A-11<br>A-12 |
| GELHAR, L.W. | New Mexico Institute of Mining and Technology<br>Campus Station<br>Socorro, NM 87801<br>(505) 835-5307 | 40- 1 | A-15<br>A-16 |
| | | 63- 2 | A-21a<br>A-23 |
| | | 21- 1 | A-9<br>A-12 |
| | | 21- 5 | A-9<br>A-12 |
| GEVERS, M. | Laboratory of Automatics and Systems Analysis<br>University of Louvain<br>1348 Louvain-la-Neuve<br>Belgium | 12-32 | A-2a |
| GIESEL, W. | Bundesanstalt fur Geowissenschaften und Rohstroffe<br>Hannover 51, P.O. 51 1 53<br>F.R. Germany | 13- 2 | A-2b |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| GOBLET, P. | Centre d'Informatique Geologique<br>Ecole des Mines de Paris<br>35, rue Saint-Honore<br>77305 Fontainebleau<br>France | 22- 7 | A-10a<br>A-12 |
| GOODWILL, I. | Dept. of Civil Engineering<br>The University<br>Leeds LS2 9JT<br>United Kingdom | 12-49<br>12-27 | A-2a<br>A-2a |
| GRANNEMANN, N.G. | Geology Department<br>University of Missouri<br>Columbia, MO 65201 | 12-40 | A-2a |
| GRANT, S. | UCLA<br>405 Hilgard Avenue<br>Los Angeles, CA 90024 | 63- 7 | A-21a<br>A-23 |
| GRIFFIN, J.D. | U.S. Geological Survey<br>Water Resources Division<br>Box 25046, Mail Stop 406<br>Denver Federal Center<br>Lakewood, CO 80225 | 12-44 | A-2a |
| GRINGARTEN, A.C. | Bureau de Recherches<br>Geologiques et Mineres<br>Service Geologique National<br>Dept. Geologie de l'Amenagement<br>B.P. 6009 - 45018 Orleans Cedex<br>France | 30- 2 | A-13<br>A-14 |
| GROVE, D. | U.S. Geological Survey<br>Box 25046, Mail Stop 413<br>Denver Federal Center<br>Lakewood, CO 80225 | 23-14 | A-11<br>A-12 |
| GUPTA, S.K. | Water Resources Center<br>University of California<br>Room 475 APB-3<br>Davis, CA 95616 | 22- 4 | A-10a<br>A-12 |
| GUVANASEN, V. | Post Office, James Cook University of North Queensland<br>Queensland, 4811<br>Australia | 12-43 | A-2a |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| HAIMES, Y. | Water Resources Systems<br>Engineering Program<br>Room 400, Wickenden Building<br>Cleveland, Ohio 44106<br>(216) 368-4076 | 70- 5 | A-24a<br>A-25 |
| | | 70-14u | A-24b<br>A-25 |
| | | 63-13 | A-21b<br>A-23 |
| | | 61-10 | A-19<br>A-23 |
| | | 63-12 | A-21b<br>A-23 |
| HAITJEMA, H.M. | University of Technology<br>Delft<br>The Netherlands | 18- 4 | A-7 |
| HALLIFAX, P. | Sir M. MacDonald & Partners<br>Demeter House, Station Road<br>Cambridge, CB1 2RS<br>United Kingdom | 12- 9 | A-2a |
| HAMDAN, A. | The University of Illinois<br>Champaign, Illinois 61820 | 63- 6 | A-21a<br>A-23 |
| HAMON, G. | Institut de Mecanique de Grenoble<br>B.P. 53 - Centre de Tri<br>38041 - Grenoble Cedex<br>France | 30- 4 | A-13<br>A-14 |
| HANKS, R.J. | Dept. of Soils and Meteorology<br>Utah State University<br>Logan, Utah 84321 | 22- 3 | A-10a<br>A-12 |
| HARA, Y. | Chiba Prefectural Research Institute<br>for Environmental Pollution (CRIEP)<br>Inage-Kaigan 3-5, Chiba 281<br>Japan | 40- 4 | A-15<br>A-16 |
| HARADA, K. | Kokusai Aerial Surveys, Co., LTD.<br>Asahigaoka 3, Hino<br>Tokyo 191<br>Japan | 40- 2 | A-15<br>A-16 |
| | | 40- 4 | A-15<br>A-16 |
| HARE, R. | General Electric - TEMPO<br>P.O. Drawer QQ<br>Santa Barbara, CA 93102 | 30- 3 | A-13<br>A-14 |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| HASSAN, A. | California Dept. of Water Resources<br>849 South Broadway<br>Los Angeles, CA 90014<br>(213) 620-4107 | 21- 2 | A-9<br>A-12 |
| HAUSZ, W. | General Electric - TEMPO<br>P.O. Drawer QQ<br>Santa Barbara, CA 93102 | 30- 3 | A-13<br>A-14 |
| HAVERKAMP, R. | Institut de Mecanique de Grenoble<br>B.P. 53 - Centre de Tri<br>38041 - Grenoble Cedex<br>France | 30- 4<br>23- 9 | A-13<br>A-14<br>A-11<br>A-12 |
| HEFEZ, E. | Dept. of Computer Sciences<br>Haifa University<br>Haifa<br>Israel | 12-14<br>70- 2 | A-2a<br>A-24a<br>A-25 |
| HELM, D.C. | U.S. Geological Survey<br>Subdistrict Office, WRD<br>Room W-2235, Federal Building<br>2800 Cottage Way<br>Sacramento, CA 95825 | 40- 5 | A-15<br>A-16 |
| HELWEG, O.J. | University of California<br>Berkeley, CA 94720 | 17- 3<br>64- 3 | A-6<br>A-22<br>A-23 |
| HENRY, J.L. | GEOHYDRAULIQUE<br>10, rue Eugene Renault<br>94700 Maisons - Alfort<br>France | 13- 7<br>13- 8<br>14-18 | A-2b<br>A-2b<br>A-3b |
| HERVE, J. | ARLAB<br>Eau et Environment<br>Sophia Antipolis - Boite Postale 15<br>06560 Valbonne - Alpes Maritimes<br>France | 12-62 | A-2a |
| HIGUCHI, S. | Chiba Prefectural Research Institute for Environmental Pollution (CRIEP)<br>Inage-Kaigan 3-5, Chiba 281<br>Japan | 40- 4 | A-15<br>A-16 |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| HOSTETLER, D.D. | Battelle, Pacific Northwest Laboratories<br>Water and Land Resources Department<br>P.O. Box 999<br>Richland, WA 99352 | 80- 5 | A-26 |
| HSIEH | Dept. of Civil Engineering<br>Princeton University<br>Princeton, NJ 05840 | 22-16 | A-10b<br>A-12 |
| HUBER, R. | SOGREAH<br>47, avenue Marie Reynoard<br>38100 - Grenoble<br>France | 13-14 | A-2b |
| HUBERT, P. | Centre de'Informatique Geologique<br>Ecole des Mines des Paris<br>35, rue Saint Honore<br>77305 - Fontainebleau<br>France | 64- 1 | A-22<br>A-23 |
| | | 64- 2 | A-22<br>A-23 |
| HUNT, B. | University of Canterbury<br>Christchurch<br>New Zealand | 12-24 | A-2a |
| HURR, R.T. | U.S. Geological Survey<br>Water Resources Division<br>Box 25046, Mail Stop 415<br>Denver Federal Center<br>Lakewood, CO 80225 | 12-42 | A-2a |
| HUYAKORN | Dept. of Civil Engineering<br>Princeton University<br>Princeton, NJ 08540 | 18- 9 | A-7 |
| IBM ISRAEL SCIENTIFIC CENTER | Technion City<br>Haifa<br>Israel | 22- 9 | A-10a<br>A-12 |
| JANSEN, G. | Battelle, Pacific Northwest Laboratories<br>Water and Land Resources Department<br>P.O. Box 999<br>Richland, WA 99352 | 23-12 | A-11<br>A-12 |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| JARDIN, P. | SOGREAH<br>47, avenue Marie Reynoard<br>38100 - Grenoble<br>France | 13-14 | A-2b |
| | | 16- 5 | A-5 |
| JIERASAK, T. | Post Office, James Cook University of North Queensland<br>Queensland, 4811<br>Australia | 12-43 | A-2a |
| JOSEPH, C. | Laboratorie de Geologie<br>C.E.R.G.H. - U.S.T.L.<br>Place Eugene Bataillon<br>34060 Montpellier Cedex<br>France | 11- 2 | A-1 |
| JOUHET, P. | SOGREAH<br>47, avenue Marie Reynoard<br>38100 - Grenoble<br>France | 13-14 | A-2b |
| | | 16- 5 | A-5 |
| KAHAN, J. | TAHAL Consulting Engineers, LTD.<br>54 IBN Gvirol Street<br>Tel-Aviv<br>Israel | 63-1u | A-21a<br>A-23 |
| KALLY, E. | TAHAL Consulting Engineers, LTD.<br>54 IBN Gvirol Street<br>Tel-Aviv<br>Israel | 63-1u | A-21a<br>A-23 |
| KAMATA, A. | Kokusai Aerial Surveys, Co., LTD.<br>Asahigaoka 3, Hino<br>Tokyo 191 | 12- 4 | A-2 |
| | | 40- 2 | A-15<br>A-16 |
| | | 40- 4 | A-15<br>A-16 |
| | | 40- 3 | A-15<br>A-16 |
| | | 11- 1 | A-1 |
| KAPULER, I. | TAHAL Consulting Engineers, LTD.<br>54 IBN Gvirol Street<br>Tel-Aviv<br>Israel | 22-13 | A-10a<br>A-12 |
| | | 18- 3 | A-7 |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| KEATING, T. | Directorate of Resource Planning<br>Southern Water Authority<br>Eastleigh House<br>Two, Market Street<br>Eastleigh, Hampshire<br>United Kingdom | 12-33 | A-2a |
| KHANJI, J. | Institut de Mecanique de Grenoble<br>B.P. 53 - Center de Tri<br>38041 - Grenoble - Cedex<br>France | 16-11 | A-5 |
| KIPP, K.L. | A.E.R.E.<br>19 West Drive<br>Harwell, Didcot<br>Oxfordshire OX 110 QF<br>United Kingdom | 12-30u | A-2a |
| | | 70- 4 | A-24a, |
| | | | A-25 |
| KITCHING. R. | Institute of Geological Sciences<br>Exhibition Road<br>London SW7<br>United Kingdom | 12-50 | A-2a |
| | | 12-20 | A-2a |
| | | 12- 1 | A-2a |
| | | 13-16 | A-2b |
| | | 14-11 | A-3a |
| KLEINECKE, D.C. | 2784 Glen Dessary Lane<br>Santa Barbara, CA 93105 | 21-2 | A-9 |
| | | | A-12 |
| | | 80- 1 | A-26 |
| | | 13-20 | A-2b |
| | | 13- 1 | A-2b |
| | | 70-13 | A-24b |
| | | | A-25 |
| KLENKE, I.M. | Institut fur Wasserwirtschaft<br>Hydrologie und landwirtschaftlichen<br>wasserbau, Technische Universitat<br>Hannover, Callinstr. 15 c,<br>Hannover<br>F.R. Germany | 12-21 | A-2a |
| KNOWLES, T.R. | Texas Water Development Board<br>Systems Engineering Divison<br>P.O. Box 13087<br>Austin, TX 78711<br>(512) 475-3606 | 12-17 | A-2a |
| | | 12-34 | A-2a |
| | | 70-12 | A-24b |
| | | | A-25 |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| KOBUS, H. | Universitat Karlsruhe<br>Kaiserstrasse 12<br>Postfach 6380<br>75 - Karlsruhe 1<br>Germany | 12-45 | A-2a |
| KONIKOW, L. | U.S. Geological Survey<br>Water Resources Division<br>Box 25046, Mail Stop 415<br>Denver Federal Center<br>Lakewood, CO 80225 | 22- 8 | A-10a<br>A-12 |
| KORGANOFF, A. | SCET-INTERNATIONAL<br>5-7, rue Bellini<br>92806, Puteaux<br>France | 12- 2 | A-2a |
| KUIPER, L.K. | Iowa Geological Survey<br>Iowa City, IO 52242 | 14-21 | A-3b |
| KUMAI, H. | Sinshu University<br>Asahi 3, Matsumoto<br>Nagano 390<br>Japan | 11- 1 | A-1 |
| KUYPERS, J.P. | Hydrological Service<br>University of Louvain<br>1348 Louvain-la-Neuve<br>Belgium | 12-32 | A-2a |
| LABADIE, J.W. | Colorado State University<br>Fort Collins, Colorado 80521 | 64- 3<br>70- 8 | A-22<br>A-23<br>A-24a<br>A-25 |
| LAMBERT, F. | Service de Radioagronomie<br>C.E.N. de Cadarache<br>13115 - St. Paul lez Durance<br>France | 23- 7 | A-11<br>A-12 |
| LANDEL, P. | Bureau de Recherches Geologiques et Mineres, Service Geologique National - Dept. Geologie de l'Amenagement<br>B.P. 6009 - 45018, Orleans Cedex<br>France | 13-15<br>30- 2 | A-2b<br>A-13<br>A-14 |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| LANTZ, R. | Intercomp Resource Development Corp.<br>1201 Dairy-Ashford<br>Suite 200<br>Houston, TX 77079<br>(713) 497-8405 | 23-15 | A-11<br>A-12 |
| | | 18-11 | A-7 |
| | | 50- 5 | A-17<br>A-18 |
| | | 23- 4 | A-11<br>A-12 |
| LARSON, S.P. | U.S. Geological Survey<br>Mail Stop 413<br>12201 Sunrise Valley Drive<br>Reston, VA 22092 | 14-20u | A-3b |
| | | 14- 3 | A-3a |
| LE CARDINAL, G. | Service de Radioagronomie<br>C.E.N. Cadarache<br>13115 - Saint Paul lez Durance<br>France | 23- 8 | A-11<br>A-12 |
| LE CLERCQ, P. | Hydrological Service<br>University of Louvain<br>1348 Louvain-la-Neuve<br>Belgium | 12-32 | A-2a |
| LEDOUX, E. | Centre d'Informatique Geologique<br>Ecole des Mines de Paris<br>35, rue St. Honore<br>77305 Fontainebleau<br>France | 23- 1 | A-11<br>A-12 |
| LESSI, J. | Centre d'Informatique Geologique<br>Ecole des Mines de Paris<br>35, rue St. Honore<br>77305 Fontainebleau<br>France | 22- 7 | A-10a<br>A-12 |
| LEVASSOR, A. | Centre d'Informatique Geologique<br>Ecole des Mines de Paris<br>35, rue St. Honore<br>77305 Fontainebleau<br>France | 61-6u | A-19<br>A-23 |
| LEVIN, O.<br>(deceased) | Technion City<br>Haifa<br>Israel | 12-55 | A-2a |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| LIDDAMENT, M.W. | Water Research Centre<br>P.O. Box 16, Henley Road<br>Medmenham Laboratories<br>Medmenham Marlow<br>Buckinghamshire SL7 2HD<br>United Kingdom | 13-14 | A-2b |
| LIN, C.L. | Water Planning & Management<br>Nova Scotia Dept. of Environment<br>P.O. Box 2107<br>Halifax, Nova Scotia<br>Canada | 12-37<br>12-39 | A-2a<br>A-2a |
| LIPPMAN, M.J. | Dept. of Geological Engineering<br>University of California<br>Berkeley, CA 94720 | 50- 4 | A-17 |
| LONGENBAUGH, R.A. | Dept. of Civil Engineering<br>Colorado State University<br>Fort Collins, CO 80523<br>(303) 491-5861 | 12-29 | A-2a |
| LONNQUIST, C.G. | Illinois State Water Survey<br>Urbana, Illinois 61801 | 12-12<br>12- 3<br>13-9u<br>22-17 | A-2a<br>A-2a<br>A-2b<br>A-10b<br>A-12 |
| LUCKEY, R. | U.S. Geological Survey<br>University of Kansas, Campus West<br>1950 Avenue A<br>Lawrence, Kansas 66044 | 63- 8 | A-21b<br>A-23 |
| LUTHIN, J. | Land, Air, and Water Resources<br>242 Veihmeyer Hall<br>University of California<br>Davis, CA 95616<br>(916) 752-0694 | 22- 4 | A-10a<br>A-12 |
| MAC MILLAN, J.R. | New Mexico Institute of Mining and Technology<br>Campus Station<br>Socorro, NM 87801 | 40- 1 | A-15<br>A-16 |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| MADDOCK, III, T. | U.S. Geological Survey<br>Mail Stop 413<br>12201 Sunrise Valley Drive<br>Reston, VA 22092<br>(703) 860-6904 | 12-53 | A-2a |
| | | 70- 7 | A-24a<br>A-25 |
| | | 61- 9 | A-19<br>A-23 |
| | | 61- 7 | A-19<br>A-23 |
| | | 61-10 | A-19<br>A-23 |
| | | 63-10 | A-21b<br>A-23 |
| MARTIN, H. | Laboratory of Geochemistry<br>University of Louvain<br>1348 Louvain-la-Neuve<br>Belgium | 12-32 | A-2a |
| MASUHARA, N. | Kokusai Aerial Surveys Co., Ltd.<br>Asahigaoka 3, Hino<br>Tokyo 191<br>Japan | 40- 2 | A-15<br>A-16 |
| MCFARLAND, J.W. | The University of Rhode Island<br>Warwick, Rhode Island 02886 | 62- 1 | A-20<br>A-23 |
| MEHLHORN, H. | Institut fur Hydromechanik<br>Universitat Karlsruhe<br>D 75 Karlsruhe 1<br>F.R. Germany | 12-45 | A-2a |
| MERCADO, M. | TAHAL Consulting Engineers, LTD.<br>54 IBN Gvirol Street<br>Tel-Aviv<br>Israel | 21- 4 | A-9<br>A-12 |
| | | 21- 3 | A-9<br>A-12 |
| MERCER, J.W. | U.S. Geological Survey<br>Mail Stop 413<br>12201 Sunrise Valley Drive<br>Reston, VA 22092 | 30- 9 | A-13<br>A-14 |
| MEREDITH, D.D. | Dept. of Civil Engineering<br>SUNY, Buffalo<br>New York 14214 | 63- 6 | A-21a<br>A-23 |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| MEYER, C. | General Electric - TEMPO<br>P.O. Drawer QQ<br>Santa Barbara, CA 93102 | 70-13 | A-24b<br>A-25 |
| MEYER, H. | Institut fur Wasserwirtschaft<br>Hydrologie und landwirtschaftlichen Wasserbau<br>Technische Universitat Hannover<br>Callinstr. 15 c, 3000 Hannover 1<br>F.R. Germany | 12-26 | A-2a |
| MIYAMOTO, N. | Nippon Koei Co., Ltd.<br>Unschisaiwai-cho 2-1-11<br>Chiyoda, Tokyo 100<br>Japan | 40- 2 | A-15<br>A-16 |
| MOBUSHERI, F. | UCLA<br>405 Hilgard Avenue<br>Los Angeles, California 90024 | 63- 7 | A-21a<br>A-23 |
| MOENCH, A.F. | U.S. Geological Survey<br>Subdistrict Office<br>855 Oak Grove Avenue<br>Menlo Park, CA 94025 | 30- 8 | A-13<br>A-14 |
| MOLZ, F.J. | Civil Engineering Department<br>Auburn University<br>Auburn, AL 36830 | 16- 4 | A-5 |
| MOREL, E.H. | Resources Division<br>Central Water Planning Unit<br>Reading Bridge House, RG1 8PS<br>United Kingdom | 12-41 | A-2a |
| MOREL-SEYTOUX, H.J. | Dept. of Civil Engineering<br>Colorado State University<br>Fort Collins, CO 80523<br>(303) 491-1101 | 12-54 | A-2a |
| MOUTONNET, P. | Service de Radioagronomie<br>C.E.N. Cadarache<br>13115 - Saint Paul lez Durance<br>France | 23- 8 | A-11<br>A-12 |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| MURAKAMI, M. | Nippon Koei Co., LTD.<br>Uchisaiwai-cho 2-1-11<br>Chiyoda, Tokyo 100<br>Japan | 40- 2 | A-15<br>A-16 |
| McLIN, S. | New Mexico Institute of Mining and Technology<br>Campus Station<br>Socorro, NM 87801 | 21- 5 | A-9<br>A-12 |
| McCRACKEN & VOSS | Dept. of Civil Engineering<br>Princeton University<br>Princeton, NJ 08540 | 50- 1 | A-17 |
| McWHORTER, D.B. | Dept. of Agricultural Engineering<br>Colorado State University<br>Fort Collins, CO 80523 | 12-47<br>22- 1 | A-2a<br>A-10a<br>A-12 |
| NAFF, R.L. | New Mexico Institute of Mining and Technology<br>Campus Station<br>Socorro, NM 87801 | 40- 1 | A-15<br>A-16 |
| NARASIMHAN, T.N. | Dept. of Geological Engineering<br>University of California<br>Berkeley, CA 94720 | 16-12<br>40- 6<br><br>16- 6<br>50- 4 | A-5<br>A-15<br>A-16<br>A-5<br>A-17 |
| NAVARRO, A. | Resources and Transportation Division<br>United Nations Station<br>New York, NY 10017 | 70- 1<br><br>13-18<br>12-64<br>12-51<br>80- 2 | A-24a<br>A-25<br>A-2b<br>A-2a<br>A-2a<br>A-26 |
| NELSON, R.W. | BCS Richland, Inc.<br>Federal Building, P.O. Box 300<br>Richland, WA 99352 | 12-60 | A-2a |
| NEUMAN, S.P. | Dept. of Hydrology & Water Resources<br>University of Arizona<br>Tucson, AZ 85717<br>(602) 884-4434 | 14- 6<br>16- 6<br>16- 7<br>14- 7 | A-3a<br>A-5<br>A-5<br>A-3a |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| NEWMAN, B.A. | Dept. of Civil and Environmental Engineering<br>Cornell University<br>Ithaca, New York 14850 | 61- 5 | A-19<br>A-23 |
| NIREI, H. | Chiba Prefectural Research Institute for Environmental Pollution (CRIEP)<br>Inage-Kaigan 3-5, Chiba 281<br>Japan | 40- 4 | A-15<br>A-16 |
| NORMAND, D. | SOGREAH<br>47, avenue Marie Reynoard<br>38100 Grenoble<br>France | 16- 5 | A-5 |
| OAKES, D. | Water Research Center<br>P.O. Box 16, Henley Road<br>Medmenham Laboratories<br>Medmenham Marlow<br>Buckinghamshire SL7 2HD<br>United Kingdom | 17- 2<br>22-14 | A-6<br>A-10a<br>A-12 |
| OKA, H. | Kokusai Aerial Surveys Co., Ltd.<br>Asahigaoka 3, Hino<br>Tokyo, 191<br>Japan | 40- 3 | A-15<br>A-16 |
| OLSTHOORN, T. | KIWA N.V.<br>Sir Winston Churchill-laan 273<br>Rijswijk<br>The Netherlands | 12-28 | A-2a |
| O'NEILL | Dept. of Civil Engineering<br>Princeton University<br>Princeton, NJ 08540 | 30- 6 | A-13<br>A-14 |
| PAGE, H.G. | U.S. Geological Survey<br>Box 25046, Mail Stop 415<br>Denver Federal Center<br>Lakewood, CO 80202 | 18- 5 | A-7 |
| PERRINE, R.L. | University of California<br>Los Angeles, CA 90024 | 70- 5 | A-24a<br>A-25 |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| PERSOONS, E. | Dept. of Agricultural Engineering<br>University of Louvain<br>1348 Louvain-la-Neuve<br>Belgium | 12-32 | A-2a |
| PETERS, J. | Hydrologic Engineering Center<br>Corps of Engineers<br>609 Second Street<br>Davis, CA 95616 | 14-1u | A-3a |
| PICKENS, J.F. | Faculty of Science<br>Dept. of Earth Science<br>University of Waterloo<br>Waterloo, Ontario N2L 3G1 Canada<br>(519) 885-1211 | 23-5u | A-11<br>A-12 |
| | | 16- 8 | A-5 |
| PILKINGTON, G. | Engineering & Water Supply Dept.<br>Box 1751 G.P.O.<br>Adelaide 5001<br>Australia | 12-41 | A-2a |
| PINDER, G.F. | Dept. of Civil Engineering<br>Princeton University<br>Princeton, NJ 08540<br>(609) 452-4602 | 12- 6 | A-2a |
| | | 22- 6 | A-10a<br>A-12 |
| | | 22- 5 | A-10a<br>A-12 |
| | | 50- 1 | A-17 |
| | | 18- 9 | A-7 |
| | | 18- 5 | A-7 |
| | | 22-16 | A-10b<br>A-12 |
| POITRINAL, D. | ARLAB<br>Eau et Environment<br>Sophia Antipolis-Boite Postale 15<br>06560 Valbonne - Alpes Maritimes<br>France | 70- 9 | A-24a<br>A-25 |
| POLATSCHEK, M. | Technion City<br>Haifa<br>Israel | 12-55 | A-2a |
| PONTIN, J.M. | Hydraulics Research Station<br>Wallingford<br>Berkshire<br>United Kingdom | 17- 2 | A-6 |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| PRAKASH, A. | Chicago, Illinois | 12-47 | A-2a |
| PRICKETT, T.A. | Illinois State Water Survey | 12-12 | A-2a |
| | Box 232 | 12- 3 | A-2a |
| | Urbana, Illinois 61801 | 13- 9u | A-2b |
| | (217) 333-1724 | 22-17 | A-10b |
| | | | A-12 |
| PRUDHOMME, P. | GEOHYDRAULIQUE | 13- 7 | A-2b |
| | 10, rue Eugene Renault | 13- 8 | A-2b |
| | 94700 Maisons-Alfort | 14-18 | A-3b |
| | France | | |
| REED, J.E. | U.S. Geological Survey | 16- 3u | A-5 |
| | 2301 Federal Office Building | 12-44u | A-2a |
| | Little Rock, AK 72201 | | |
| REHN, M. | Engineering & Water Supply Dept. | 12-41 | A-2a |
| | Box 1751 G.P.O. | | |
| | Adelaide 5001 | | |
| | Australia | | |
| REISENAUER, A. | Battelle, Pacific Northwest Laboratories | 13-19 | A-2b |
| | | 12-30u | A-2a |
| | Water & Land Resources Division | | |
| | P.O. Box 999 | | |
| | Richland, WA 99352 | | |
| REMSON, I. | Stanford University | 61- 2 | A-19 |
| | Palo Alto, California 94304 | | A-23 |
| RENNIE, A. | Post Office, James Cook University of North Queensland | 12-43 | A-2a |
| | Queensland, 4811 | | |
| | Australia | | |
| ROBERTSON, J.B. | U.S. Geological Survey | 23-13 | A-11 |
| | Subdistrict Office | | A-12 |
| | 855 Oak Grove Avenue | 23-10 | A-11 |
| | Menlo Park, CA 94025 | | A-12 |
| ROEFFS, T.G. | University of Arizona | 61- 3 | A-19 |
| | Tucson, Arizona 85721 | | A-23 |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| ROUSSELOT, D. | Bureau de Recherches<br>Geologiques et Minieres<br>Service Geologique National<br>Dept. Geologie de l'Amenagement<br>BP 6009 45018 Orleans Cedex<br>France | 13-15 | A-2b |
| RUSHTON, K.R. | Dept. of Civil Engineering<br>University of Birmingham<br>P.O. Box 363<br>Birmingham B15 2TT<br>United Kingdom | 12-18<br>12-10<br>14-12 | A-2a<br>A-2a<br>A-3a |
| SAFAI | Dept. of Civil Engineering<br>Princeton University<br>Princeton, NJ 08540 | 40- 8 | A-15<br>A-16 |
| SAGAR, B. | Hydrology Research Division<br>Inland Water Directory<br>Environment Canada<br>Ottawa, Ontario K1A OE7<br>Canada | 70- 3 | A-24a<br>A-25 |
| SALEEM, S. | Dept. of Geological Sciences<br>University of Illinois<br>Chicago, Illinois 60680<br>(312) 996-3154 | 13-11<br>63- 4 | A-2b<br>A-21a<br>A-23 |
| SARKAR, A. | (No address.<br>Contact: Y.Y. Haimes) | 63-13 | A-21b<br>A-23 |
| SAUTY, J.P. | Bureau de Recherchas<br>Geologiques et Minieres<br>Service Geologique National<br>Dept. Geologie de l'Amenagement<br>BP 6009 45018 Orleans Cedex<br>France | 13-15<br>30- 2 | A-2b<br>A-13<br>A-14 |
| SCHAUER, J. | Post Office, James Cook University<br>of North Queensland<br>Queensland, 4811<br>Australia | 12-43 | A-2a |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| SCHMIDT, G. | Bundesanstalt fur Geowissenschaften und Rohstoffe<br>(Federal Institute for Geosciences and Natural Resources)<br>3000 Hannover 51<br>P.O. Box 51 1 53<br>Hannover<br>F.R. Germany | 13- 2 | A-2b |
| SCHWARTZ, F.W. | University of Alberta<br>Edmonton, Canada | 23- 6 | A-11<br>A-12 |
| SCHWARZ, J. | TAHAL Consulting Engineers, LTD.<br>54 IBN Gvirol Street<br>Tel-Aviv<br>Israel | 22- 2 | A-10a<br>A-12 |
|  |  | 61- 1 | A-19<br>A-23 |
|  |  | 18- 2 | A-7 |
|  |  | 21- 3 | A-9<br>A-12 |
|  |  | 12-55 | A-2a |
|  |  | 63-1u | A-21a<br>A-23 |
|  |  | 63-11 | A-21b<br>A-23 |
| SEGOL, G. | Bechtel<br>250 Bloor St., E.<br>Toronto, Ontario M4W 3K5<br>Canada<br>(416) 928-1600 | 23- 3 | A-11<br>A-12 |
|  |  | 22-15 | A-10b<br>A-12 |
| SEIDEL, G. | Geology & Geophysics<br>Cns. Constitution<br>Av. Anzac Pde.<br>Canberra A.C.T. 2601<br>Australia | 13-17 | A-2b |
| SELIM, H.M. | Soil Science Department<br>University of Florida<br>Gainesville, FL 32611 | 23-17 | A-11<br>A-12 |
| SERNE, R.J. | Battelle, Pacific Northwest Laboratories<br>Water & Land Resources Division<br>Richland, WA 99352 | 23-11 | A-11<br>A-12 |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| SERVICE DE MATHEMATIQUES | Laboratoire Central DesPonts & Chaussees | 50- 6u | A-17 |
| | 58 Boulevard Lefebvre | | |
| | 75732 Paris Cedex 15 | | |
| | France | | |
| SHAH, C.R. | Central Designs Organisation | 12-13 | A-2a |
| | Secretariat Block No. 10 | | |
| | Gandhinagar 382010 | | |
| | India | | |
| SHALEV, Z. | TAHAL | 63- 5 | A-21a |
| | 54 IBN Gvirol Street | | A-23 |
| | Tel-Aviv | | |
| | Israel | | |
| SHAMIR, U. | Israel Institute of Technology | 12-14 | A-2a |
| | Haifa | 18- 1 | A-7 |
| | Israel | 70- 2 | A-24a |
| | | | A-25 |
| SHAPIRO, A. | Dept. of Civil Engineering | 22-11 | A-10a |
| | Princeton University | | A-12 |
| | Princeton, NJ 08540 | | |
| SHARP, J. | Geology Department | 14- 4 | A-3a |
| | University of Missouri | 12-40 | A-2a |
| | Columbia, MO 65201 | 50- 3 | A-17 |
| | (314) 882-2121 | | |
| SHIBASAKI, T. | Research Group for Water Balance | 12- 4 | A-2 |
| | 182 Fujigane | 40- 2 | A-15 |
| | Tsurugashima, Saitama 350-02 | | A-16 |
| | Japan | 40- 4 | A-15 |
| | | | A-16 |
| | | 40- 3 | A-15 |
| | | | A-16 |
| | | 11- 1 | A-1 |
| SIMPSON, E . | Department of Hydrology | 12-52 | A-2a |
| | University of Arizona | 61- 3 | A-19 |
| | Tucson, AZ 85721 | | A-23 |
| | (602) 631-7137 | | |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FORM APPENDIX A |
|---|---|---|---|
| SOREY, M.L. | U.S. Geological Survey<br>Subdistrict Office<br>855 Oak Grove Avenue<br>Menlo Park, CA 94025 | 30- 7<br><br>50- 4 | A-13<br>A-14<br>A-17 |
| STARK, K.P. | Post Office, James Cook University<br>of North Queensland<br>Queensland, 4811, Australia | 12-43 | A-2a |
| STONER, R.F. | Sir M. MacDonald & Partners<br>Demeter House<br>Station Road<br>Cambridge CB1 2RS<br>United Kingdom | 12- 9 | A-2a |
| SUMMERS, K. | Tetra Tech, Inc.<br>Environmental Systems<br>Engineering<br>3700 Mt. Diablo Boulevard<br>Lafayette, CA 94549 | 17- 3 | A-6 |
| SUNADA, D. | Dept. of Civil Engineering<br>Colorado State University<br>Fort Collins, CO 80523<br>(303) 491-6095 Main Campus<br>(303) 491-8666 Foothills Campus | 12-47<br>12-29<br>12-46<br><br>22- 1 | A-2a<br>A-2a<br>A-2a<br><br>A-10a<br>A-12 |
| SYLVESTRE, M. | Gouvernement du Quebec<br>Ministere des Richesses Naturelles<br>Hotel du Gouvernement<br>1640 Boulevard de l'Entente<br>Quebec, Quebec G1S 4N6<br>Canada | 14-13 | A-3a |
| TANJI, K.K. | Land, Air, and Water Resources<br>242 Veihmeyer Hall<br>University of California<br>Davis, CA 95616 | 22- 4 | A-10a<br>A-12 |
| TAYLOR, O.J. | U.S. Dept. of the Interior<br>Water Resources Division<br>1400 Independence Road, Stop 200<br>Rolla, MO 65401 | 63- 8 | A-21b<br>A-23 |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| TERRY, J.E. | U.S. Geological Survey<br>2301 Federal Office Building<br>Little Rock, AR 72201 | 16- 3u | A-5 |
| THIEM, H. | Institut fur Wasserwirtschaft<br>Hydrologie und landwirtschaftlichen Wasserbau<br>Technische Universitat Hannover<br>Callinstr. 15 c, 3000 Hannover<br>F.R. Germany | 22-10u | A-10a<br>A-12 |
| THRAILKILL, J. | Department of Geology<br>Water Resources Institute<br>University of Kentucky<br>Lexington, KY 40506 | 12-63 | A-2a |
| TILMAN, E. | Dept. of Agricultural Engineering<br>University of Louvain<br>1348 Louvain-la-Neuve<br>Belgium | 12-32 | A-2a |
| TODD, D.K. | Dept. of Civil Engineering<br>University of California<br>Berkeley, CA 94720<br>(415) 642-5525 | 70-13 | A-24b<br>A-25 |
| | | 30- 3 | A-13<br>A-14 |
| TOMLINSON, L.M. | Dept. of Civil Engineering<br>University of Birmingham<br>P.O. Box 363<br>Birmingham B15 2TT<br>United Kingdom | 12-18 | A-2a |
| | | 12-10 | A-2a |
| TRESCOTT, P. | U.S. Geological Survey<br>Mail Stop 413<br>12201 Sunrise Valley Drive<br>Reston, VA 22092 | 14-20u | A-3b |
| | | 14- 3 | A-3a |
| TRIPPLER, K. | Bundesanstalt fur Geowissenschaften und Rohstoffe<br>(Federal Institute for Geosciences and Natural Resources)<br>P.O. Box 51 1 53<br>3000 Hannover 51,<br>F.R. Germany | 13- 2 | A-2b |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| UPDEGRAFF, C.D. | New Mexico Institute of Mining and Technology<br>Campus Station<br>Socorro, NM 87801 | 21- 5 | A-9<br>A-12 |
| VANCON, J.P. | SGAL, 204, route de Schirmeck<br>67200 Strasbourg<br>France | 12- 7 | A-2a |
| VAN DEN AKKER, C. | Municipal Waterworks of Amsterdam<br>Condensatorweg 54<br>Amsterdam-Sloterdijk<br>The Netherlands | 12-57<br>12-58<br>16- 2<br>12-56 | A-2a<br>A-2a<br>A-5<br>A-2a |
| VANDENBERG, A. | Hydrology Research Division<br>Water Resources Branch<br>Environment Canada<br>Place Vincent Massey<br>Ottawa, Ontario K1A 0E7<br>Canada | 12- 5<br>12-61 | A-2a<br>A-2a |
| VANDENBEUSCH, M. | Bureau de Recherches Geologiques et Mineres, Service Geologique<br>National - Dept. Geologie de l'Amenagement<br>B.P. 6009 - 45018, Orleans Cedex<br>France | 13-15 | A-2b |
| VAN DER VEER, P. | Rijkswaterstaat<br>Data Processing Division<br>Nijverheidsstraat 1<br>Rijswijk<br>The Netherlands | 18- 7u | A-7 |
| VAN DER WEERT, R. | National Institute for Water Supply<br>P.O. Box 150<br>Leidschendam<br>The Netherlands | 15- 1<br>16- 1 | A-4<br>A-5 |
| VAN DOORNE, W. | Institute for Land and Water Management Research (ICW)<br>Staringgebouw, Wageningen<br>The Netherlands | 15- 3 | A-4 |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| VAN GENUCHTEN | Dept. of Civil Engineering<br>Princeton University<br>Princeton, NJ 08540 | 22-12 | A-10a<br>A-12 |
| VAUCLIN, M. | Institut de Mecanique de Grenoble<br>B.P. 53 - Centre de Tri<br>38041 Grenoble, Cedex<br>France | 16-11<br>30- 4 | A-5<br>A-13<br>A-14 |
| VERGE, M.J. | Dept. of Earth Sciences<br>University of Waterloo<br>Waterloo, Ontario<br>Canada | 16-13u | A-5 |
| VERRULJT, A. | Dept. of Hydraulic Engineering<br>Delft University of Technology<br>Delft<br>The Netherlands<br>(015) 13 32 22 | 12-11<br>40- 7 | A-2a<br>A-15<br>A-16 |
| VOLKER, R.E. | Engineering Research Center<br>Foothills Campus<br>Colorado State University<br>Fort Collins, CO 80521 | 12-43 | A-2a |
| WALLICK, E.I. | Groundwater Division<br>Alberta Research Council<br>11315 - 87 Avenue<br>Edmonton, Alberta T6J 2W3<br>Canada<br>(403) 433-6421 | 70-10 | A-24b<br>A-25 |
| WILLIS, R. | Cornell University<br>Ithaca, New York 14850 | 61- 5 | A-19<br>A-23 |
| | | 62- 2 | A-20<br>A-23 |
| | | 62- 3 | A-20<br>A-23 |
| WILSDON, J. | State Rivers and Water Supply<br>Commission, Victoria<br>590 Orrong Road<br>Armdale, 3143<br>Victoria<br>Australia | 14-14 | A-3b |

| NAME | ADDRESS | MODEL REPORT NUMBER | ASSOCIATED TABLE FROM APPENDIX A |
|---|---|---|---|
| WILSON, J. | Parsons Laboratory for Water Resources and Hydrodynamics<br>Dept. of Civil Engineering<br>Building 48-209<br>Massachusetts Institute of Technology<br>Cambridge, Massachusetts 02139 | 21- 2 | A-9<br>A-12 |
| WIND, G.P. | Institute for Land and Water Research (ICW)<br>Staringgebouw<br>Wageningen<br>The Netherlands | 15- 3 | A-4 |
| WISMER, D.A. | University of California<br>Los Angeles, CA 90024 | 70- 5 | A-24a<br>A-25 |
| WITHERSPOON, P. | Dept. of Civil Engineering<br>University of California<br>Berkeley, CA 94720<br>(415) 642-5525 | 14- 6 | A-3a |
| | | 14- 7 | A-3a |
| WOLZACK, J. | Div. Hydraulique Souterraine-Drainage<br>DTGREF, Pard de Tourvoie<br>92160 Antony<br>France | 12-16 | A-2a |
| | | 15- 2 | A-4 |
| YOUNG, R.A. | Resources for the Future<br>1755 Massachusetts Ave., N.W.<br>Washington, DC 20036 | 63- 9 | A-21b<br>A-23 |
| | | 61- 8 | A-19<br>A-23 |
| YU, W. | Dept. of Statistics & Operations Research<br>Grad. School of Business<br>University of Texas<br>Austin, Texas | 63-12 | A-21b<br>A-23 |